
Surrogate Reactions using STARS at GAMMASPHERE

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LLNL**

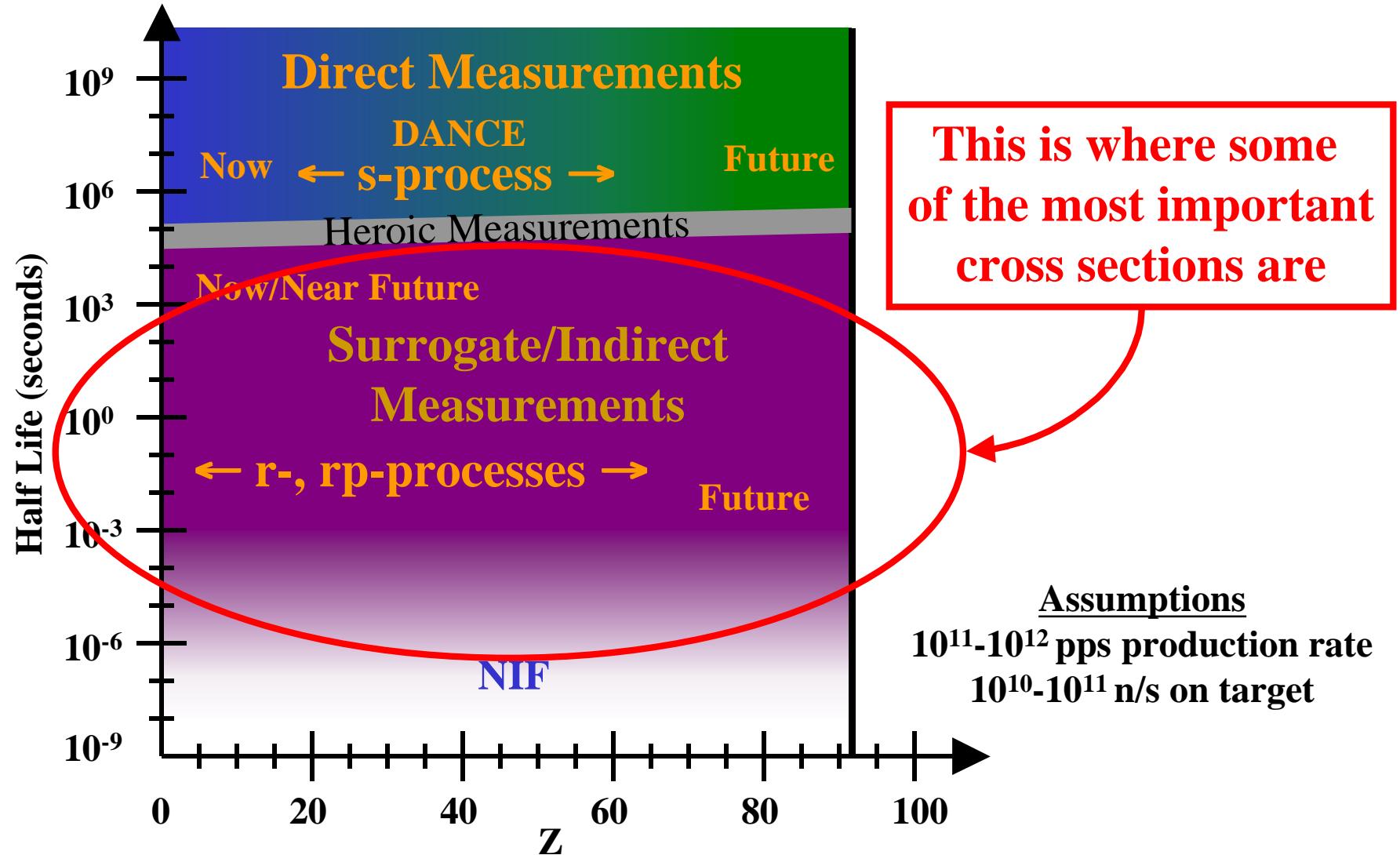


**Workshop on Nuclear Reactions on Unstable Nuclei
and the Surrogate Reaction Technique
January 13, 2004**

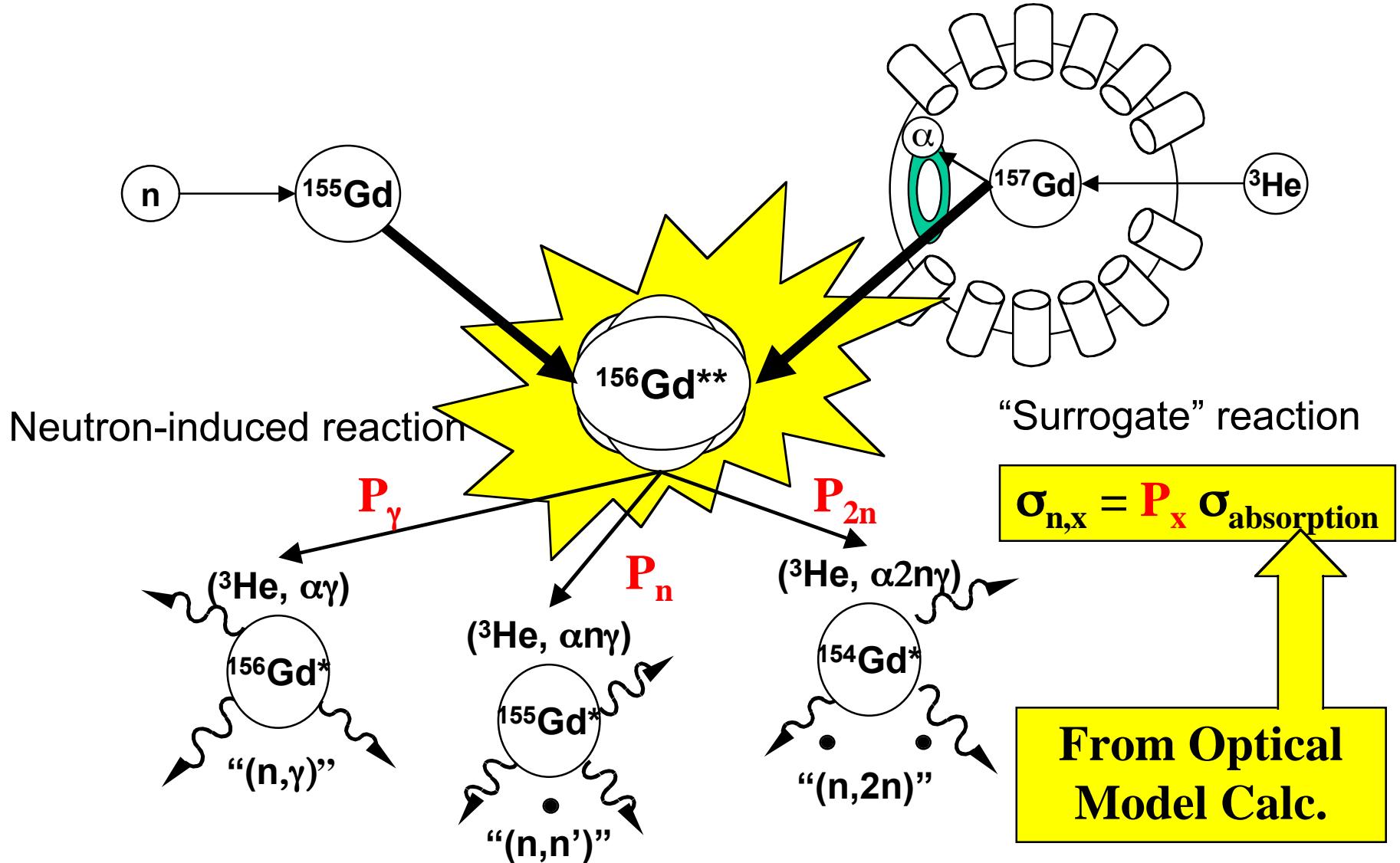
This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

Unclassified

Many neutron-induced reaction cross sections on radioactive nuclei will be determined indirectly



Surrogate neutron-induced reactions using charged particle beams - Our First Test Case



Silicon Telescope Array for Reaction Studies coupled to GAMMASPHERE (A. Schiller)



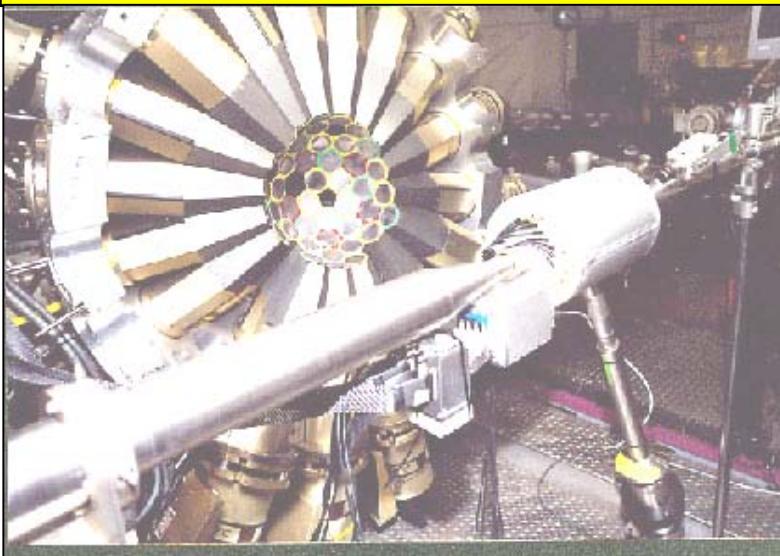
- **Proposal:**
 - Measure Level Density and γ -ray strength functions as a function of E_x , J^π and K in ^{156}Gd using “Oslo Technique”
 - Test feasibility of surrogate reaction technique (secondary)
- **Reaction:**
 - $^{157}\text{Gd}(\text{He}^3, \alpha) ^{156}\text{Gd}$ at $E(\text{He}^3) = 45 \text{ MeV}$
- **3 day run at an Average Current of 0.2-0.3 pnA**
 - Concerns about neutron damage of detectors (foundless)

First experiment completed: 4/02

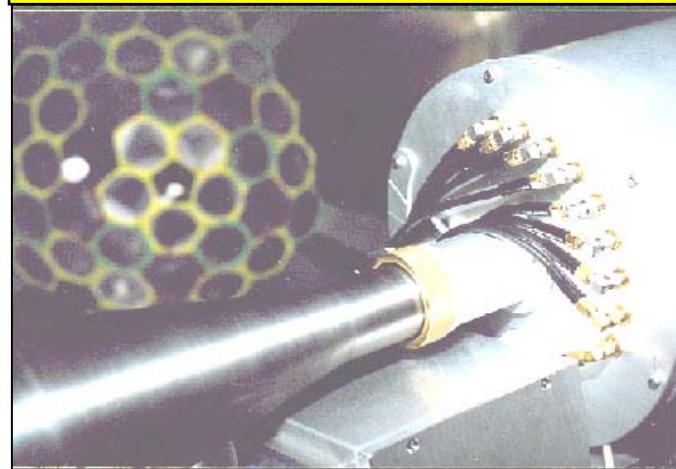
STARS at GAMMASPHERE



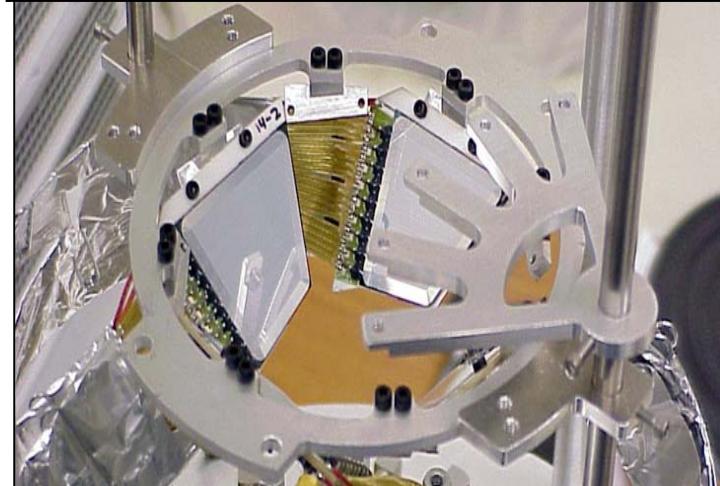
STARS at GAMMASPHERE



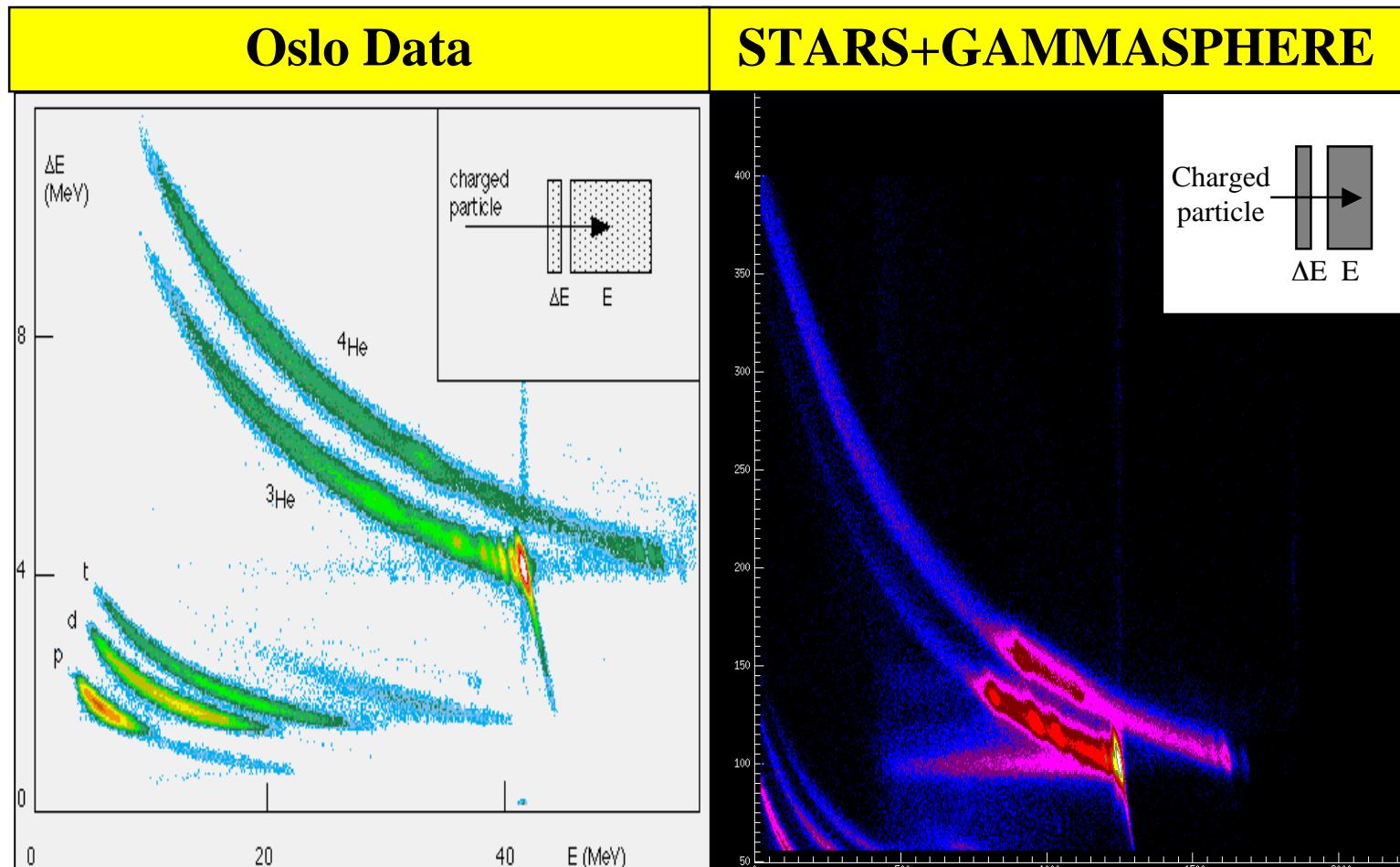
Back of STARS chamber



Target ladder + Detectors

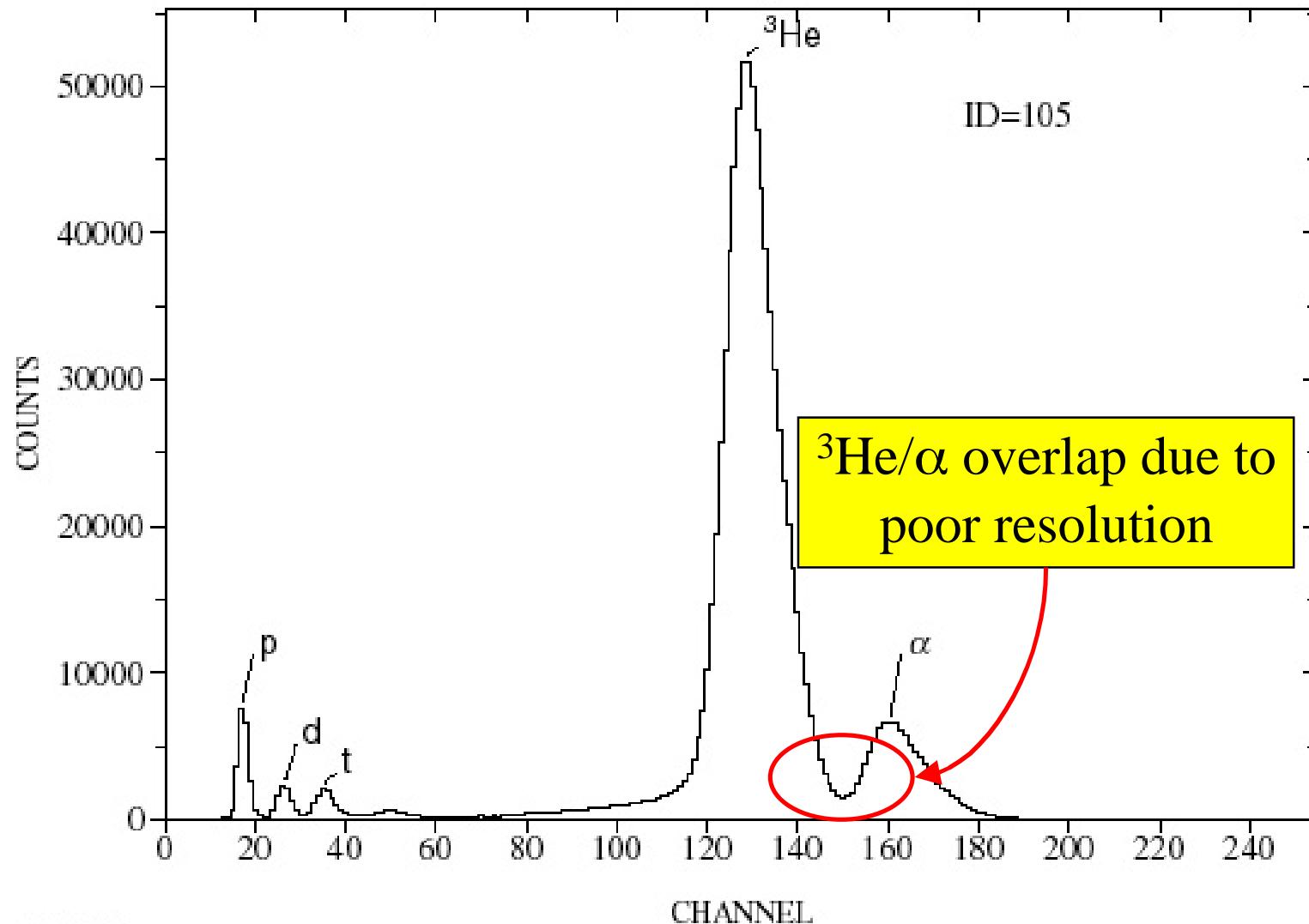


Step 1: Use the ΔE -E Matrix to get range curve for particle-id

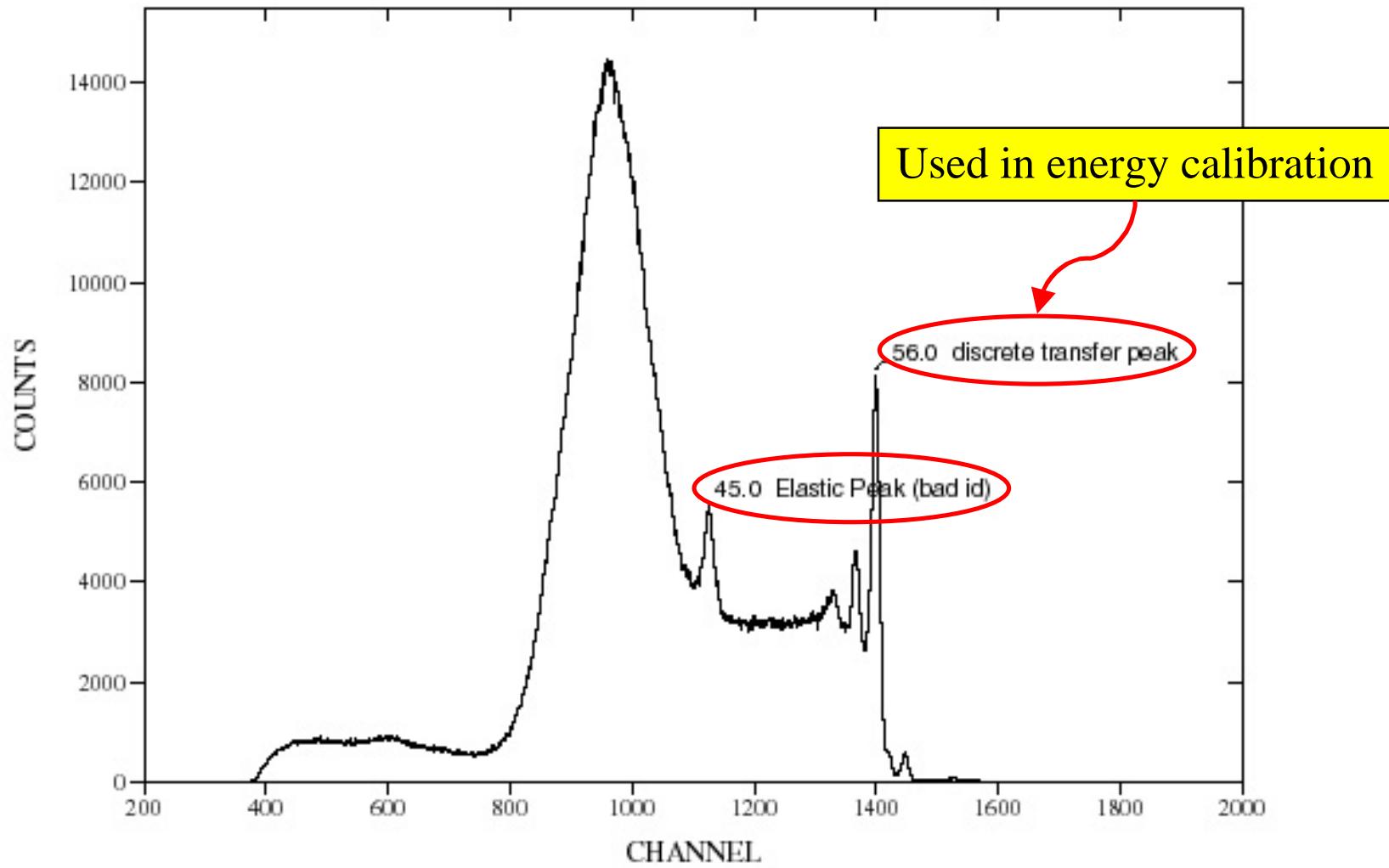


High CFD threshold cut-off low- ΔE events

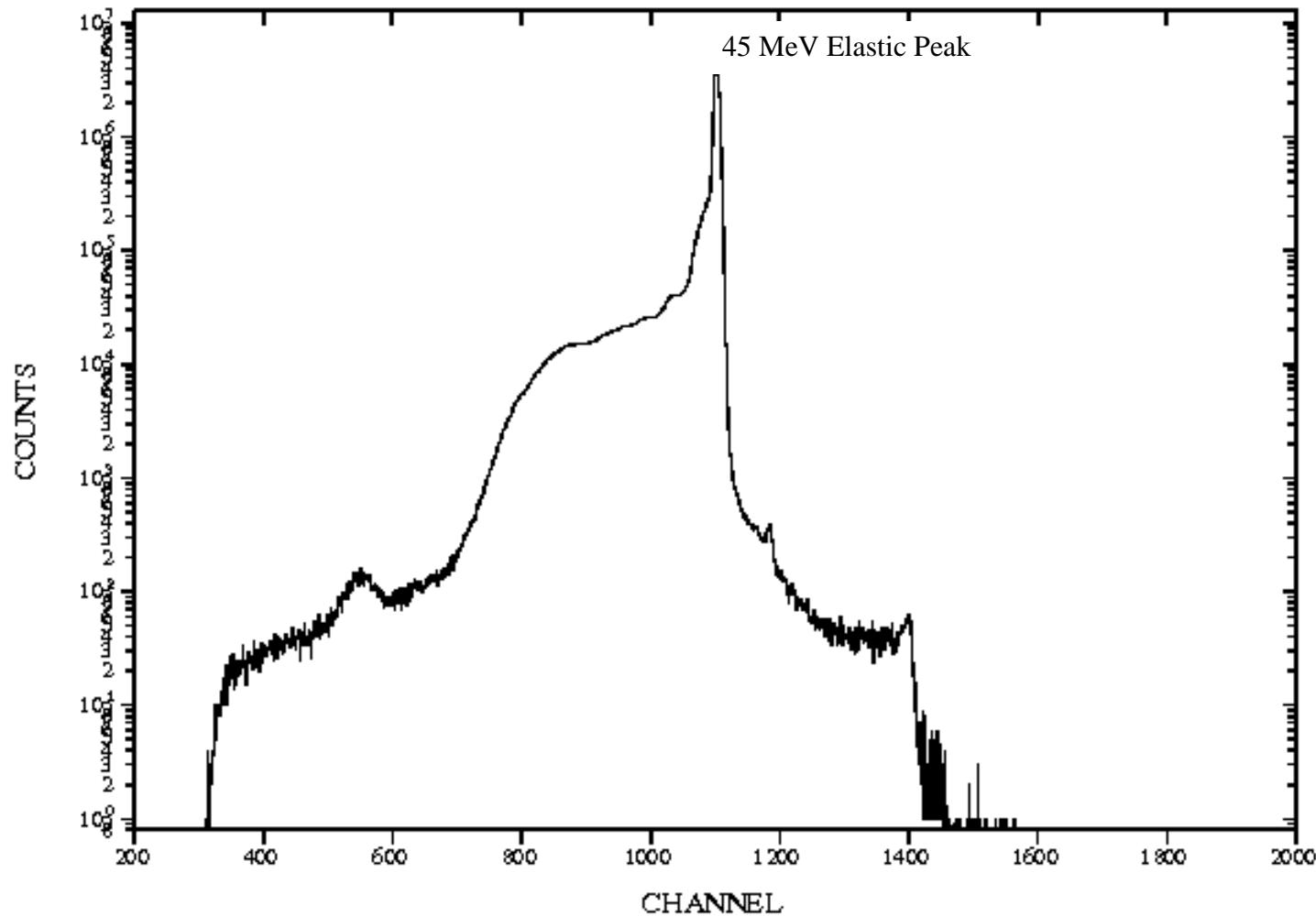
Step 2: Use Range Curves to gate on particle type



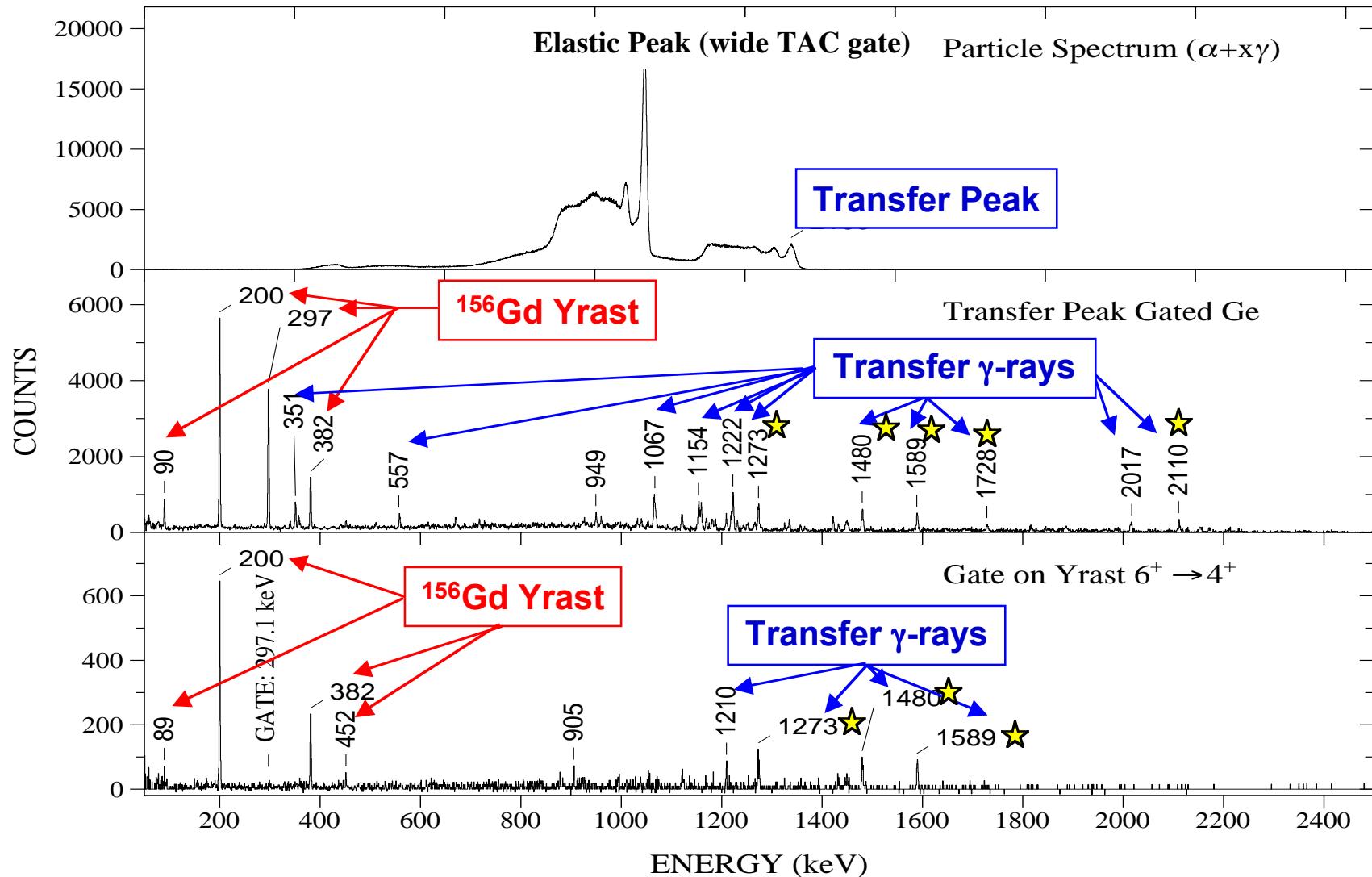
Step 3: Obtain total energy spectrum for ${}^4\text{He}/{}^3\text{He}$



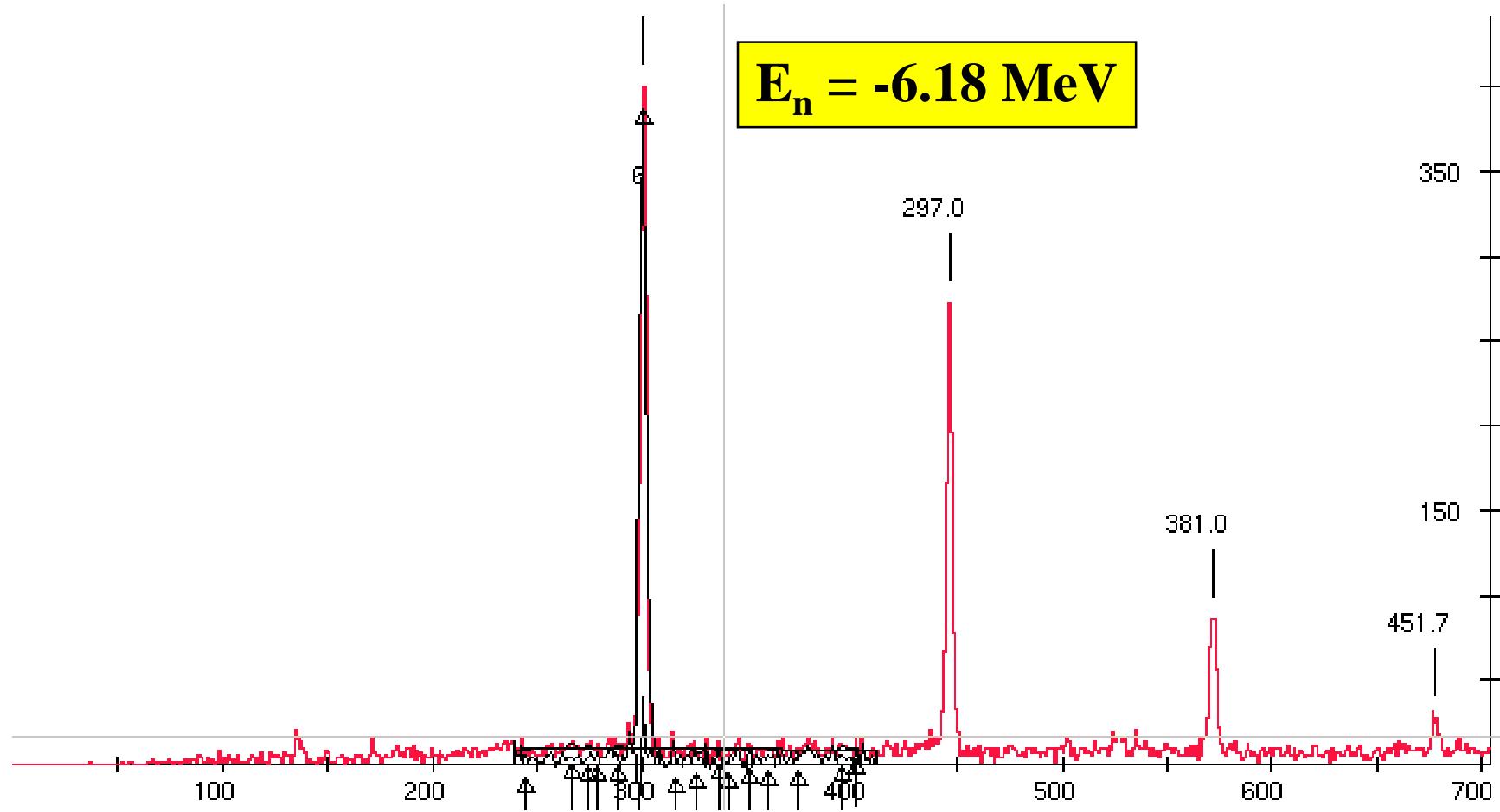
Total Energy Spectrum for ${}^3\text{He}$



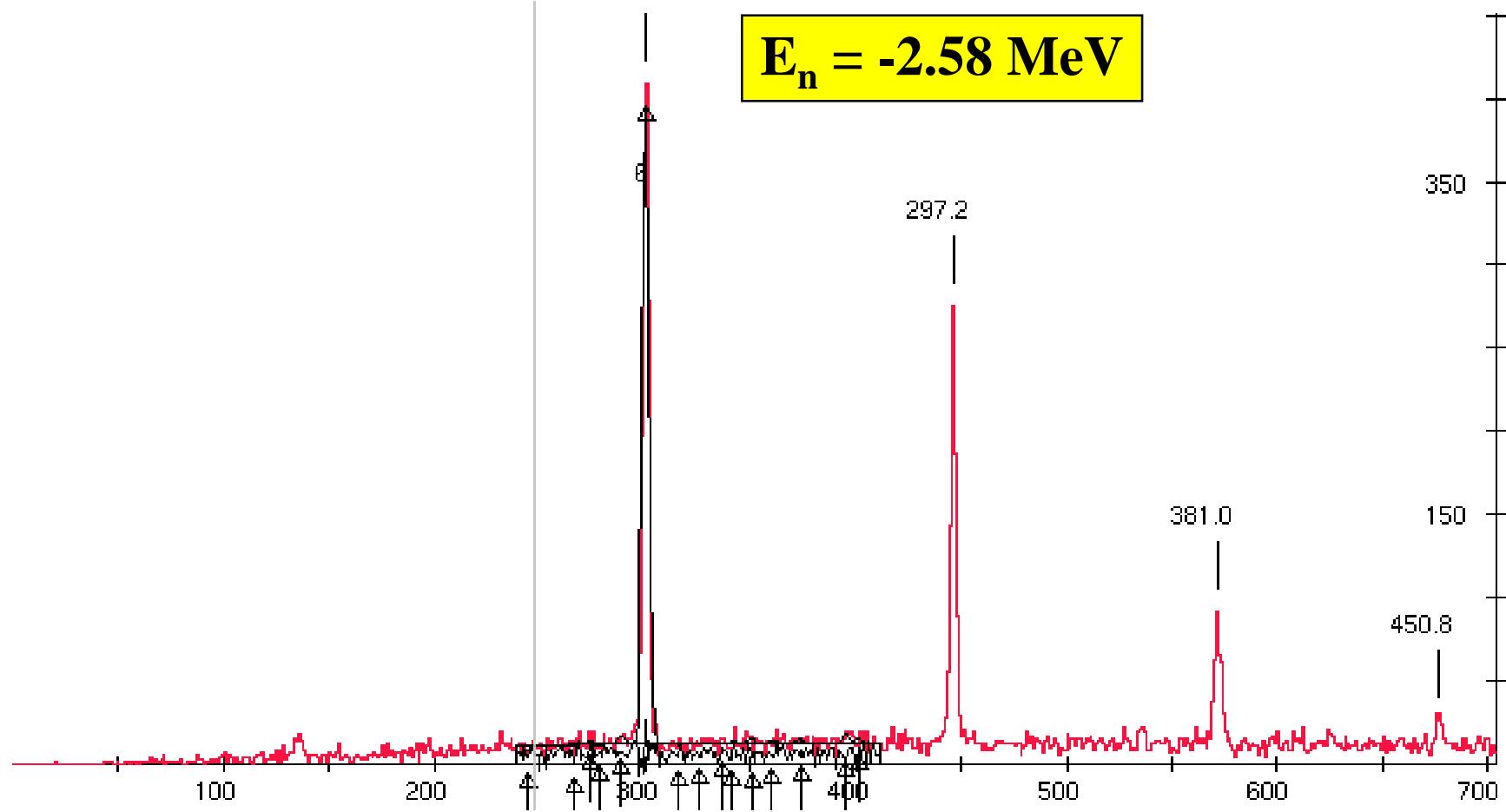
Particle- γ coincident data



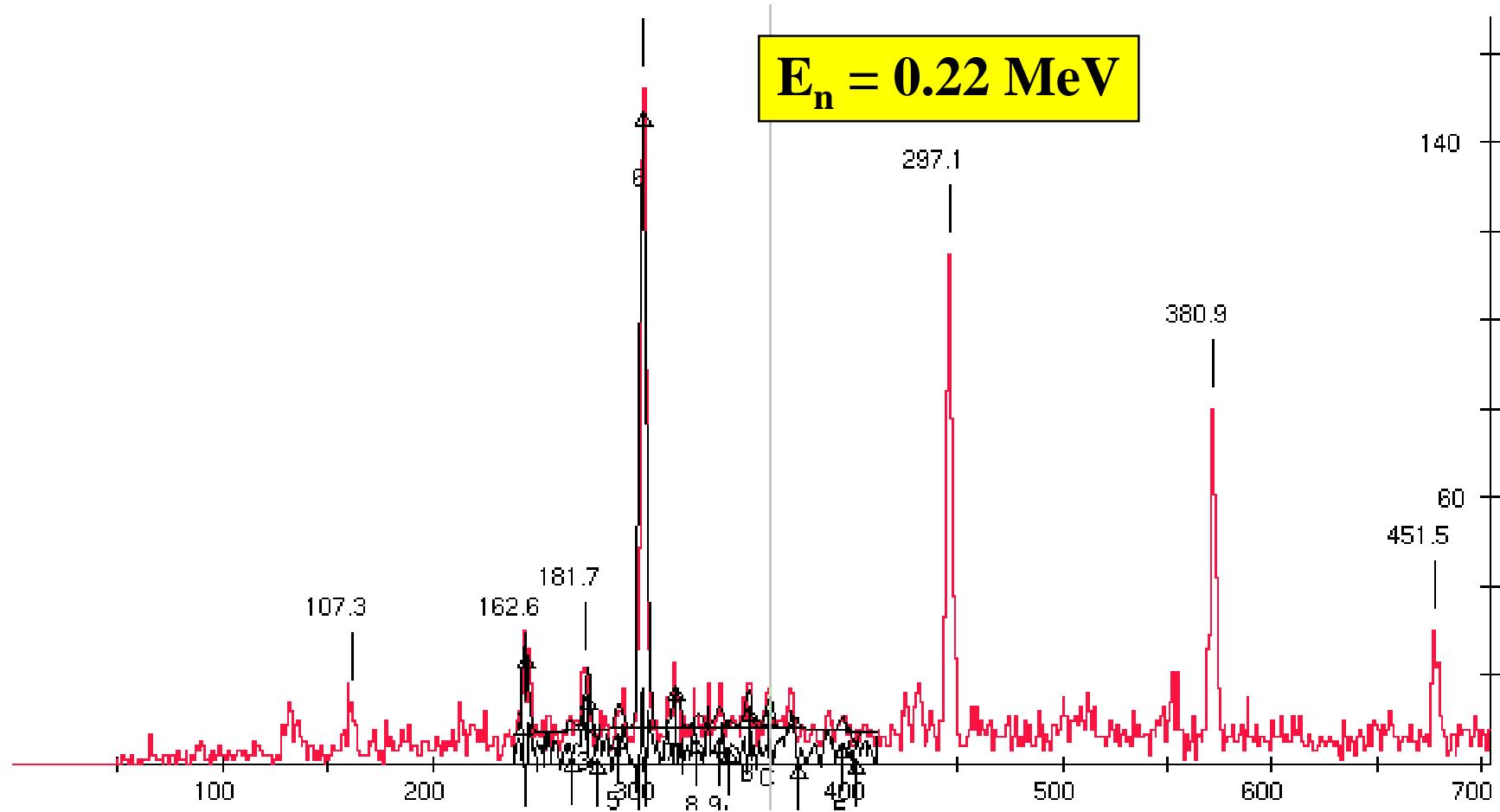
Gamma-spectrum in coincidence with different energy slices



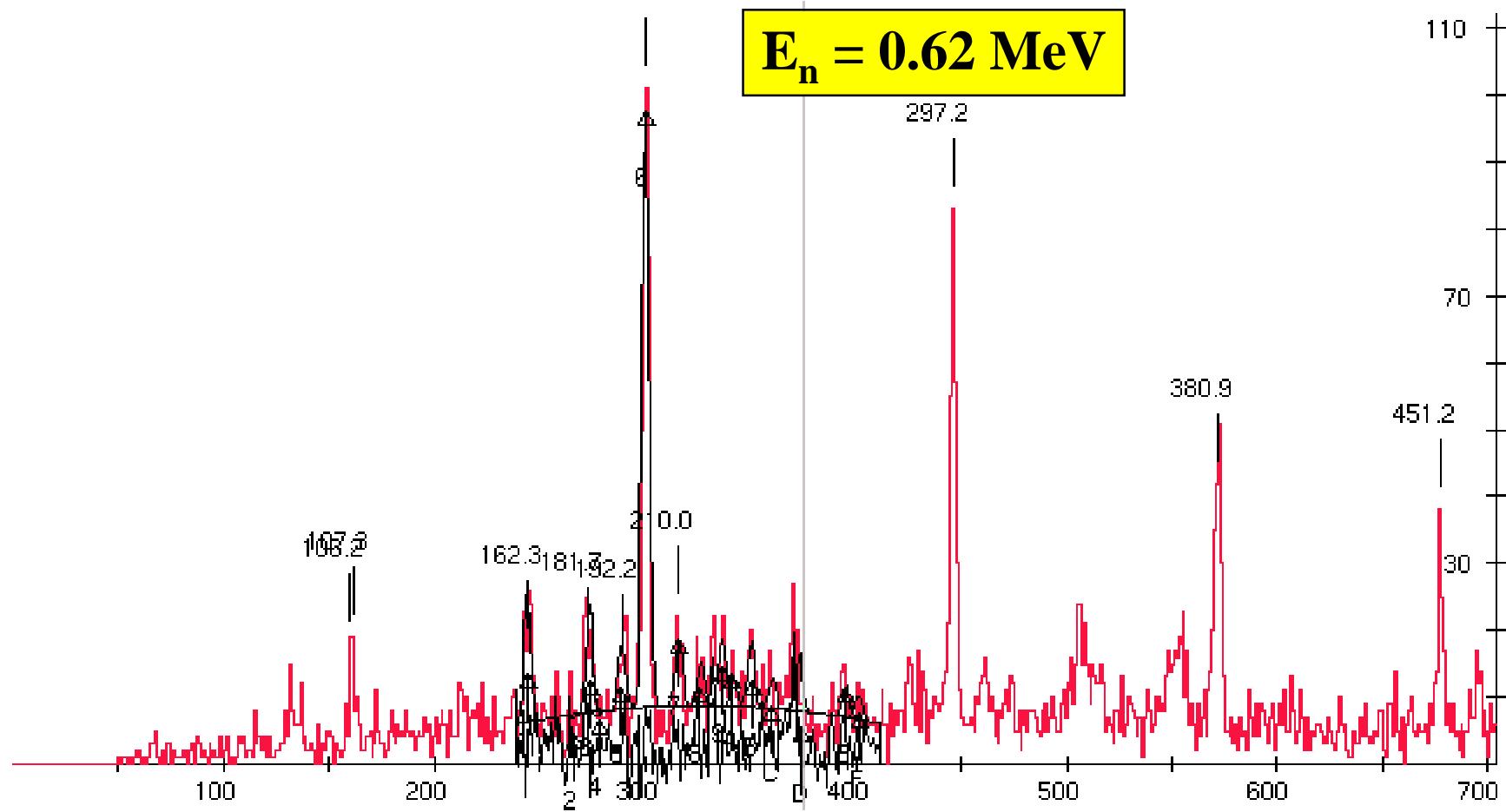
Gamma-spectrum in coincidence with different energy slices



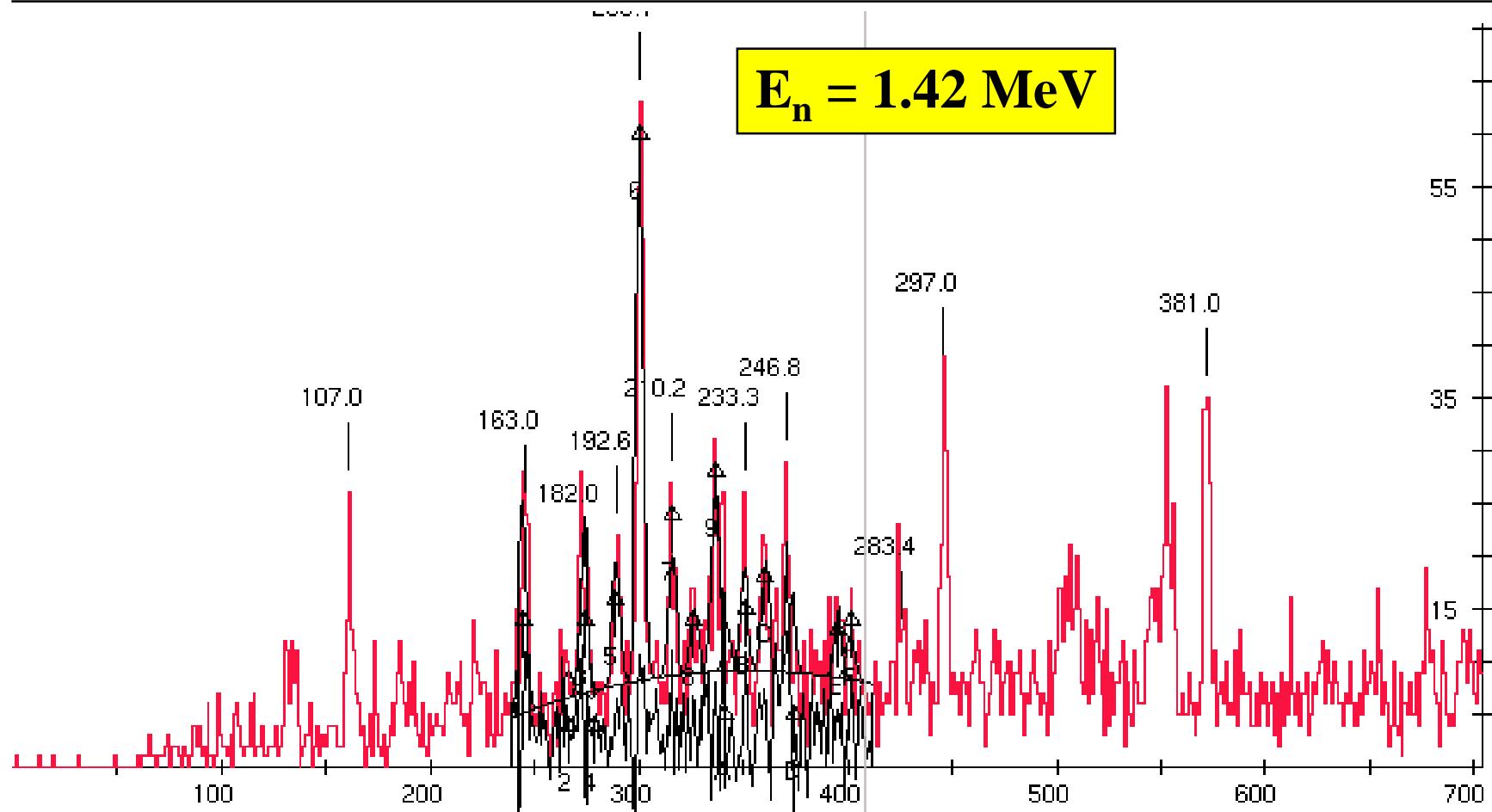
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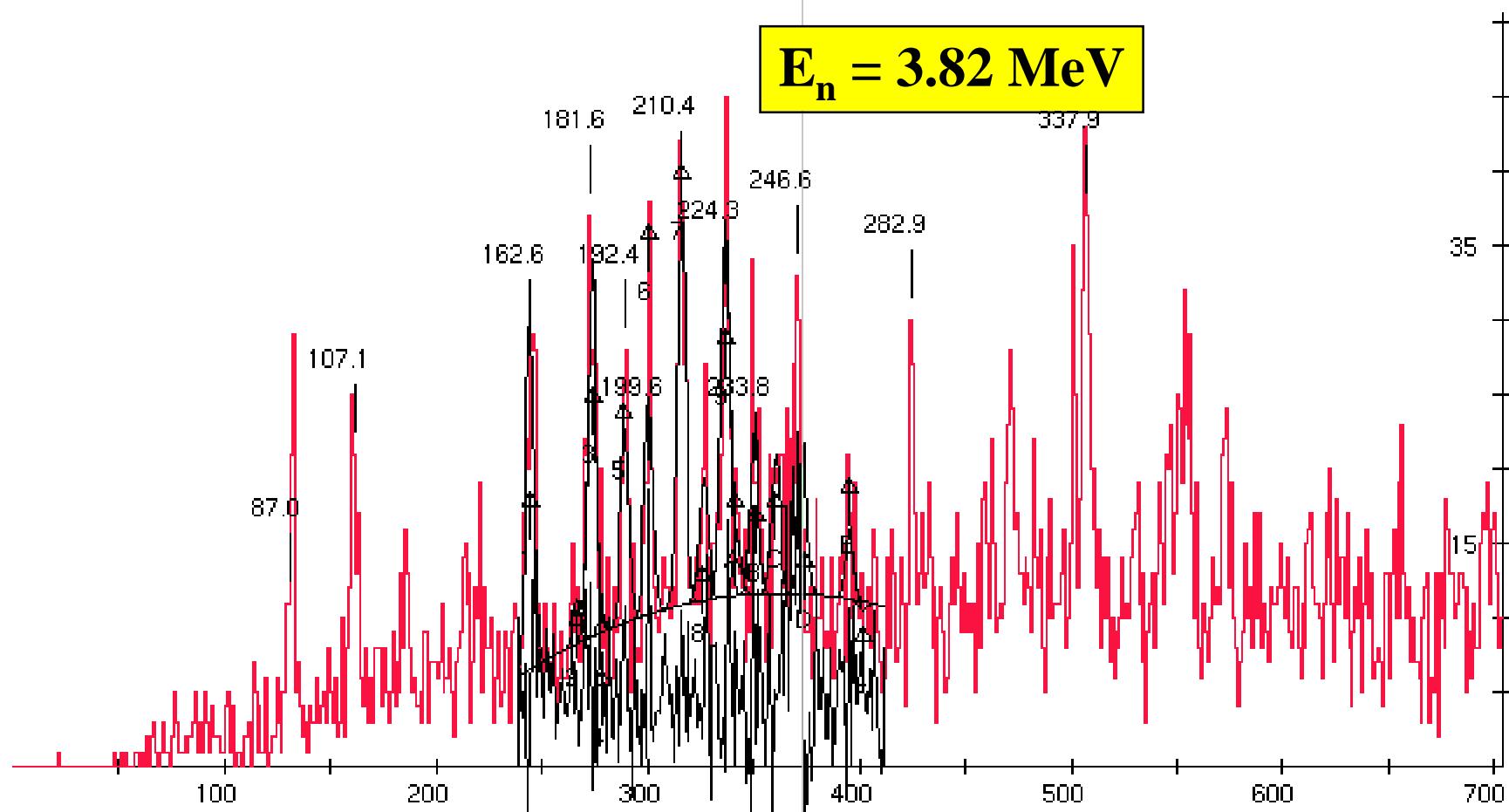
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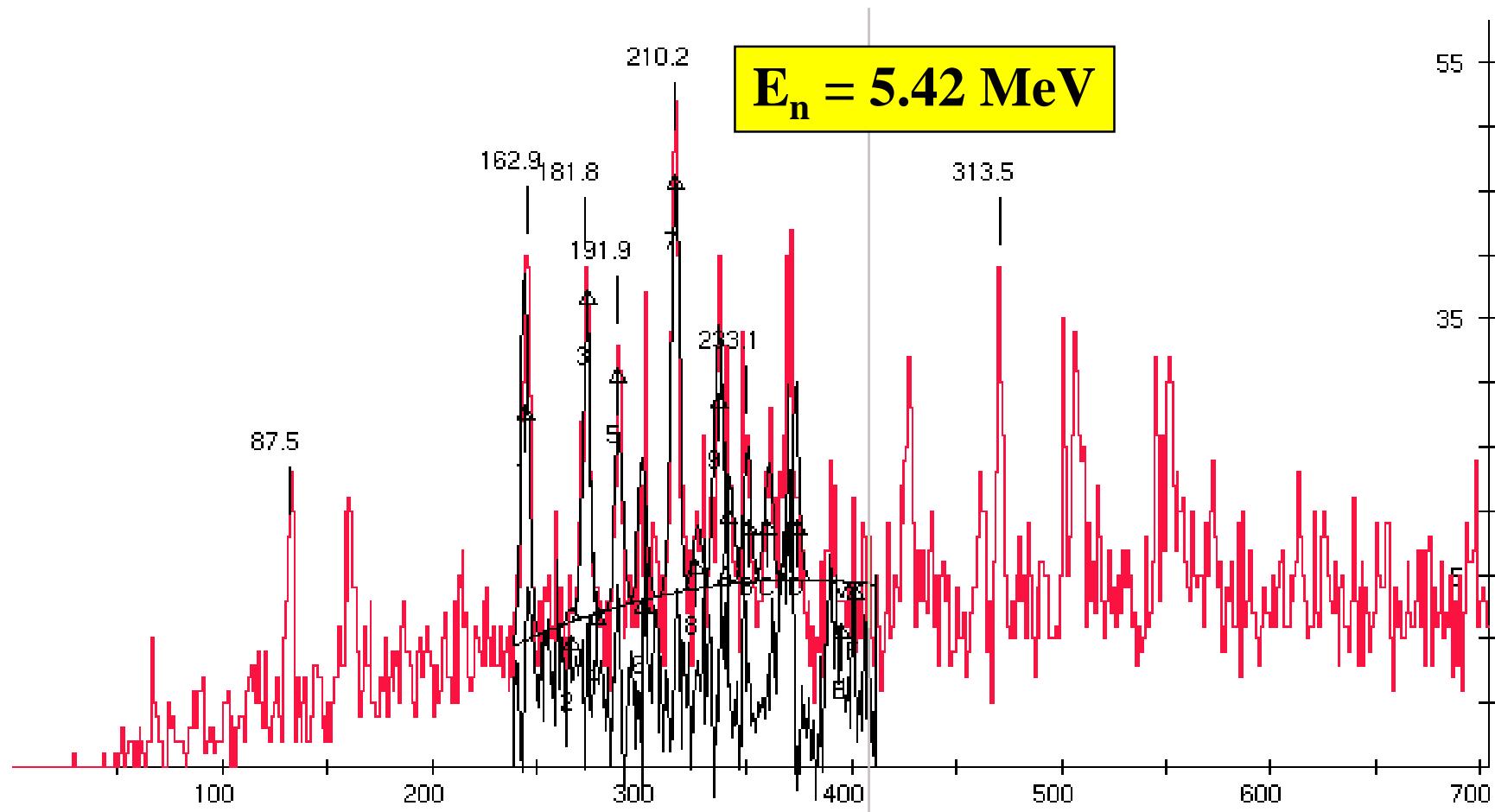
Gamma-spectrum in coincidence with different energy slices



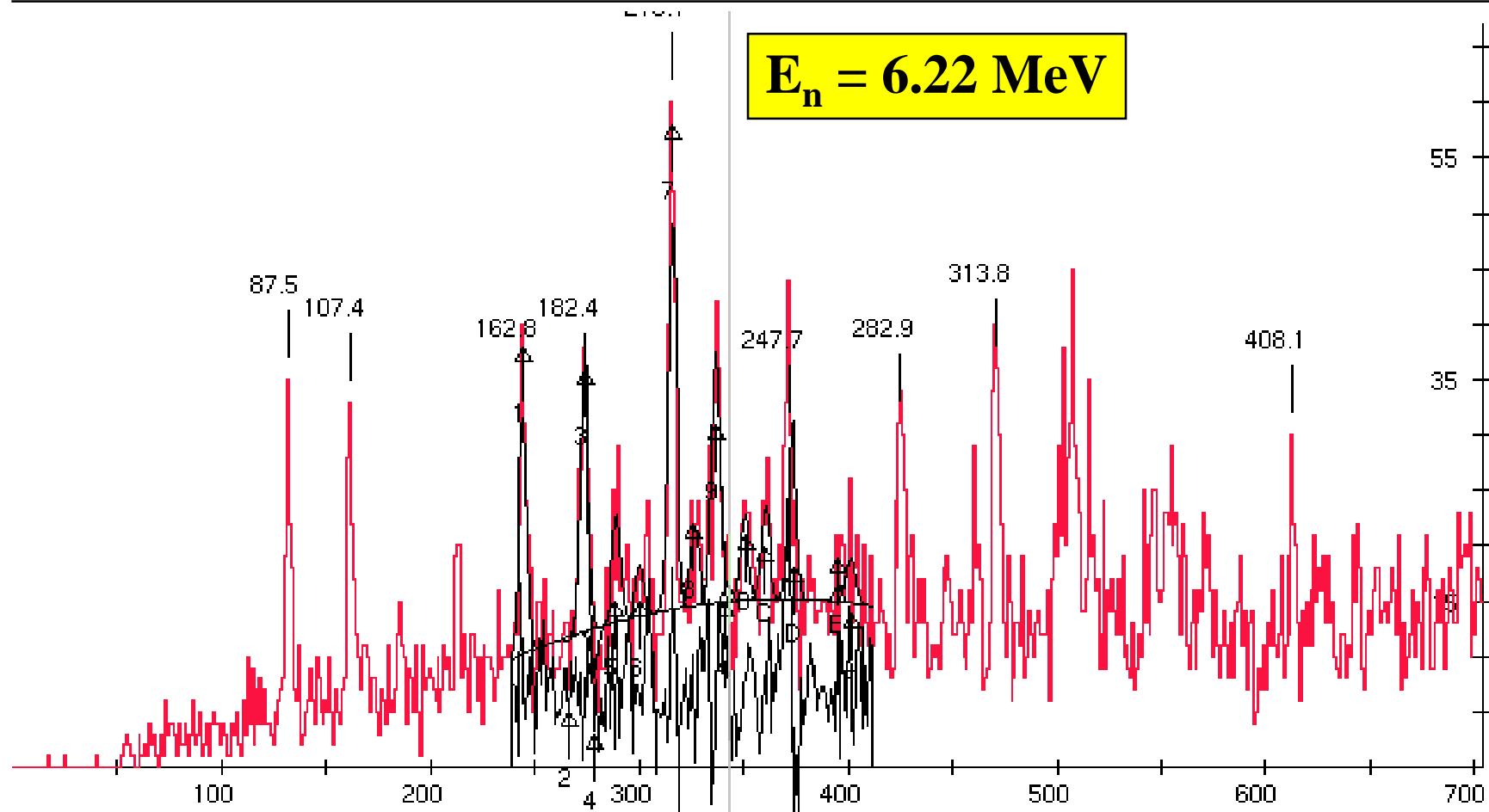
Gamma-spectrum in coincidence with different energy slices



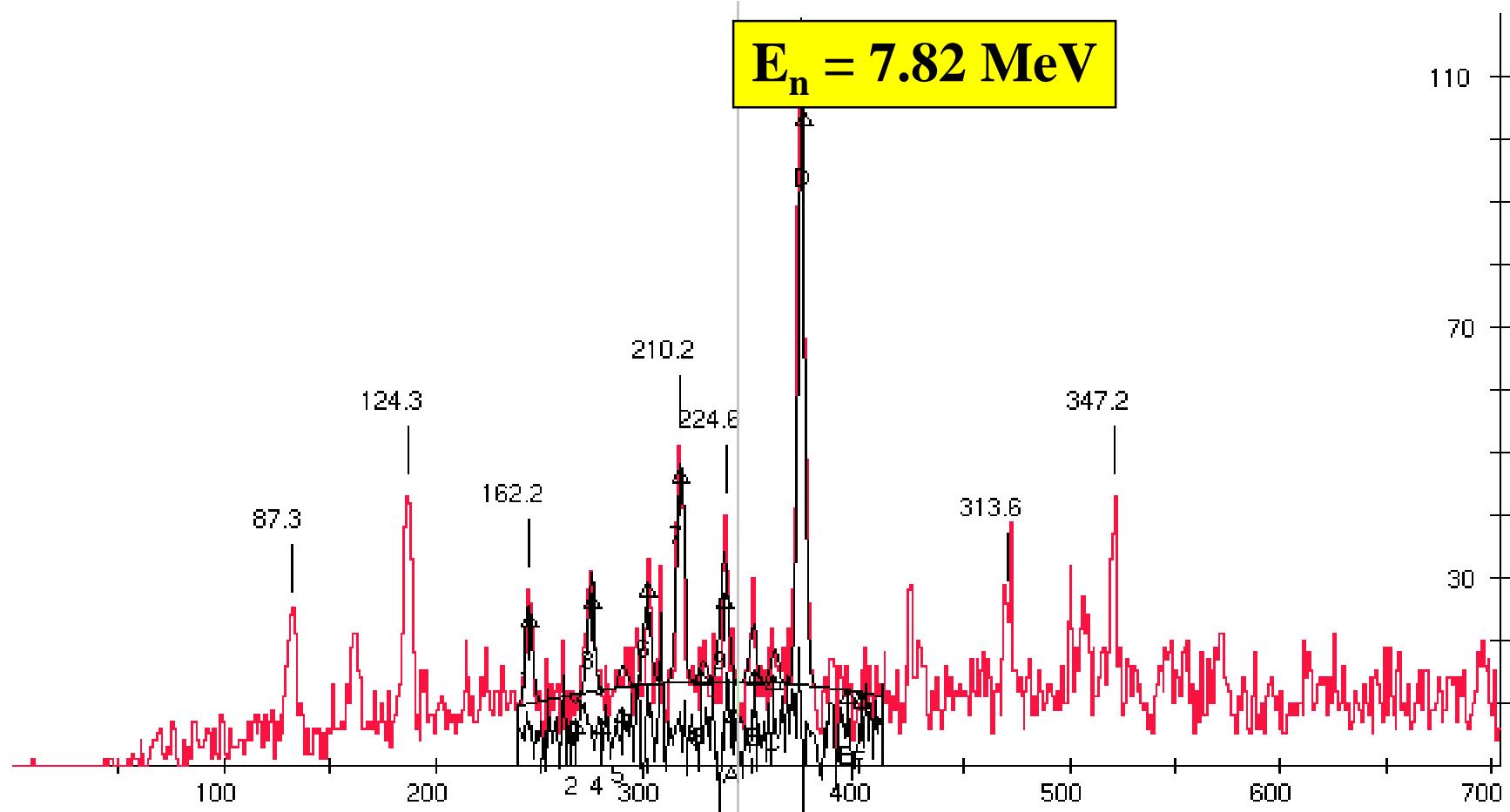
Gamma-spectrum in coincidence with different energy slices



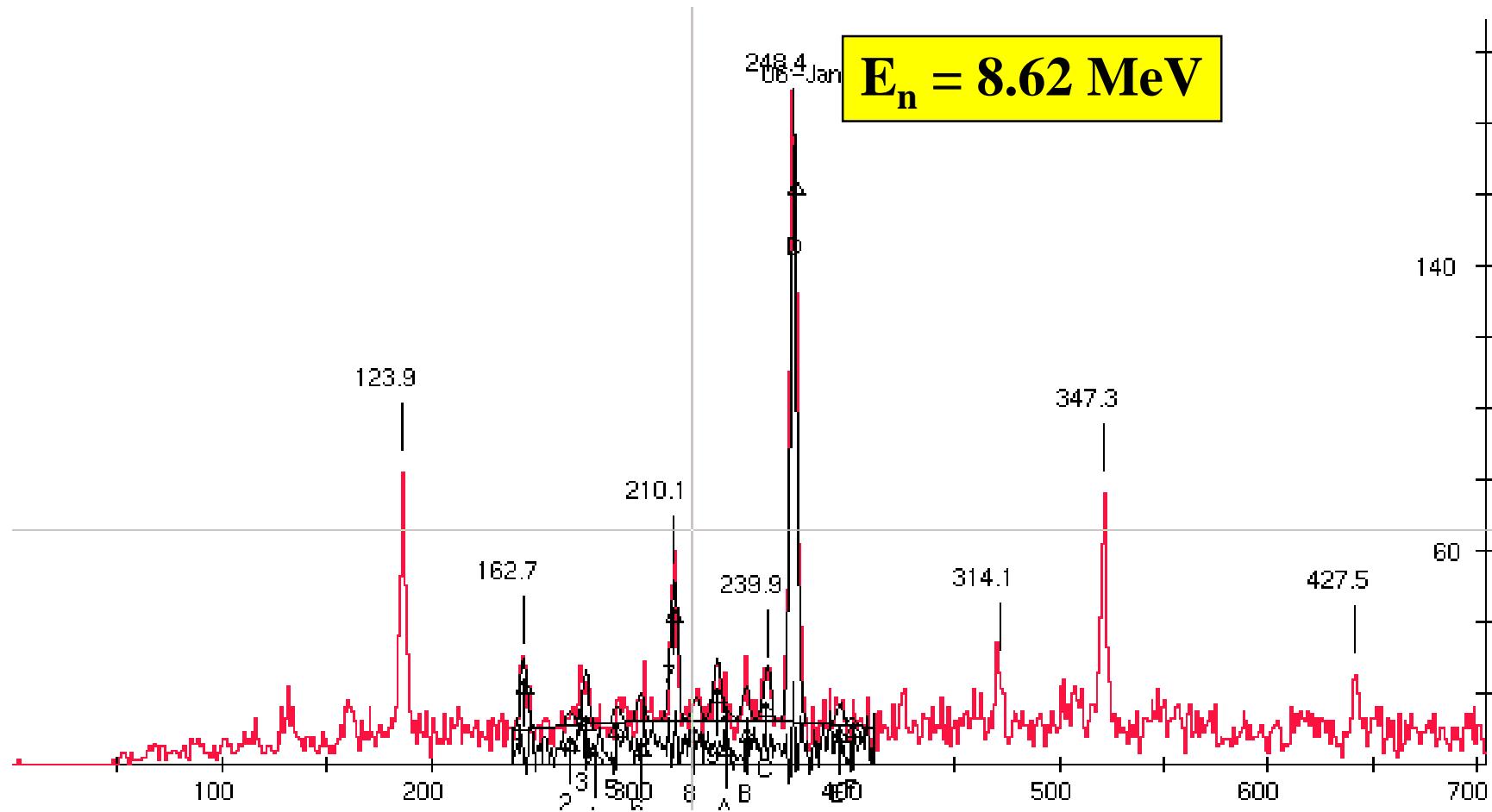
Gamma-spectrum in coincidence with different energy slices



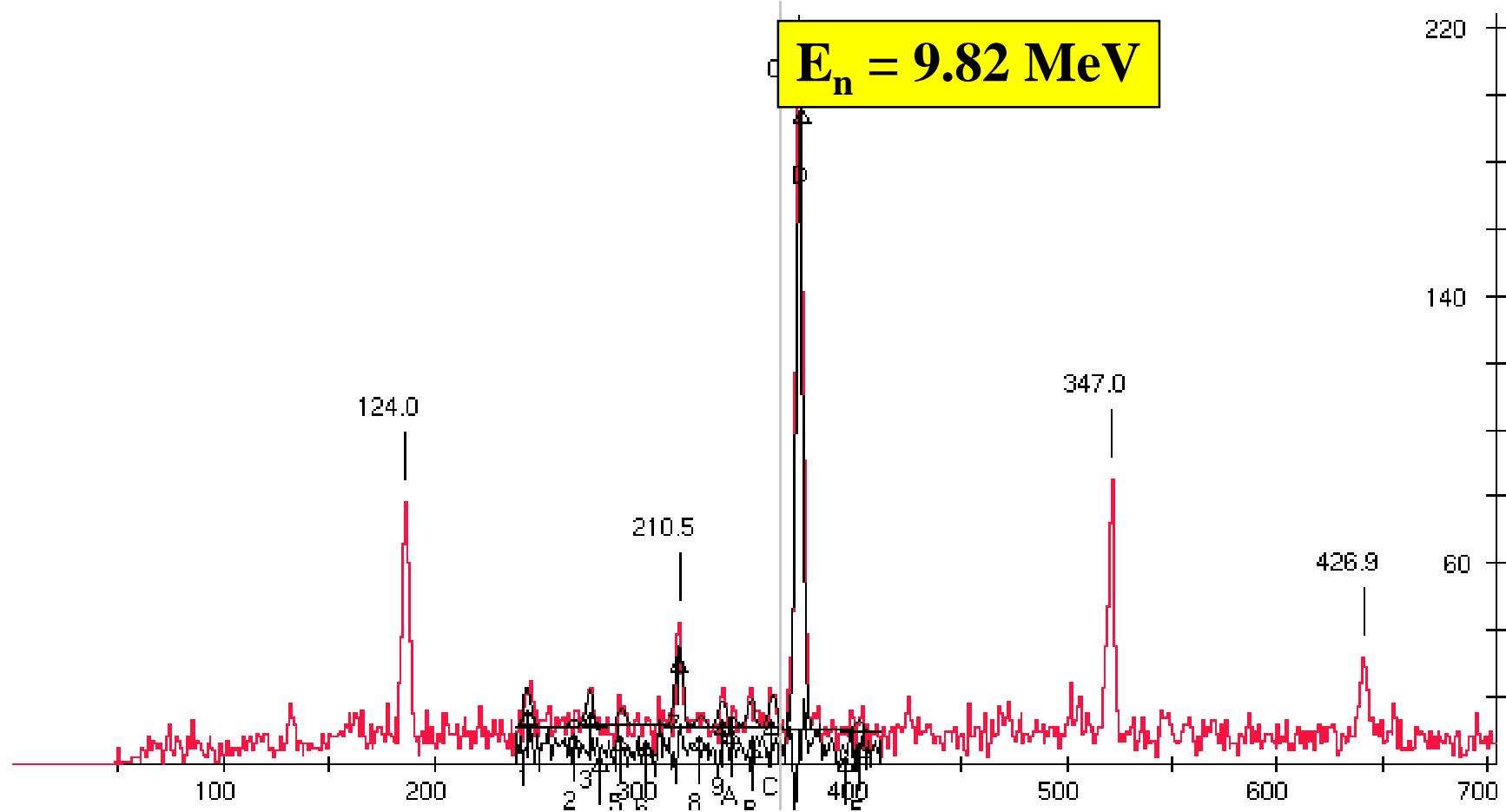
Gamma-spectrum in coincidence with different energy slices



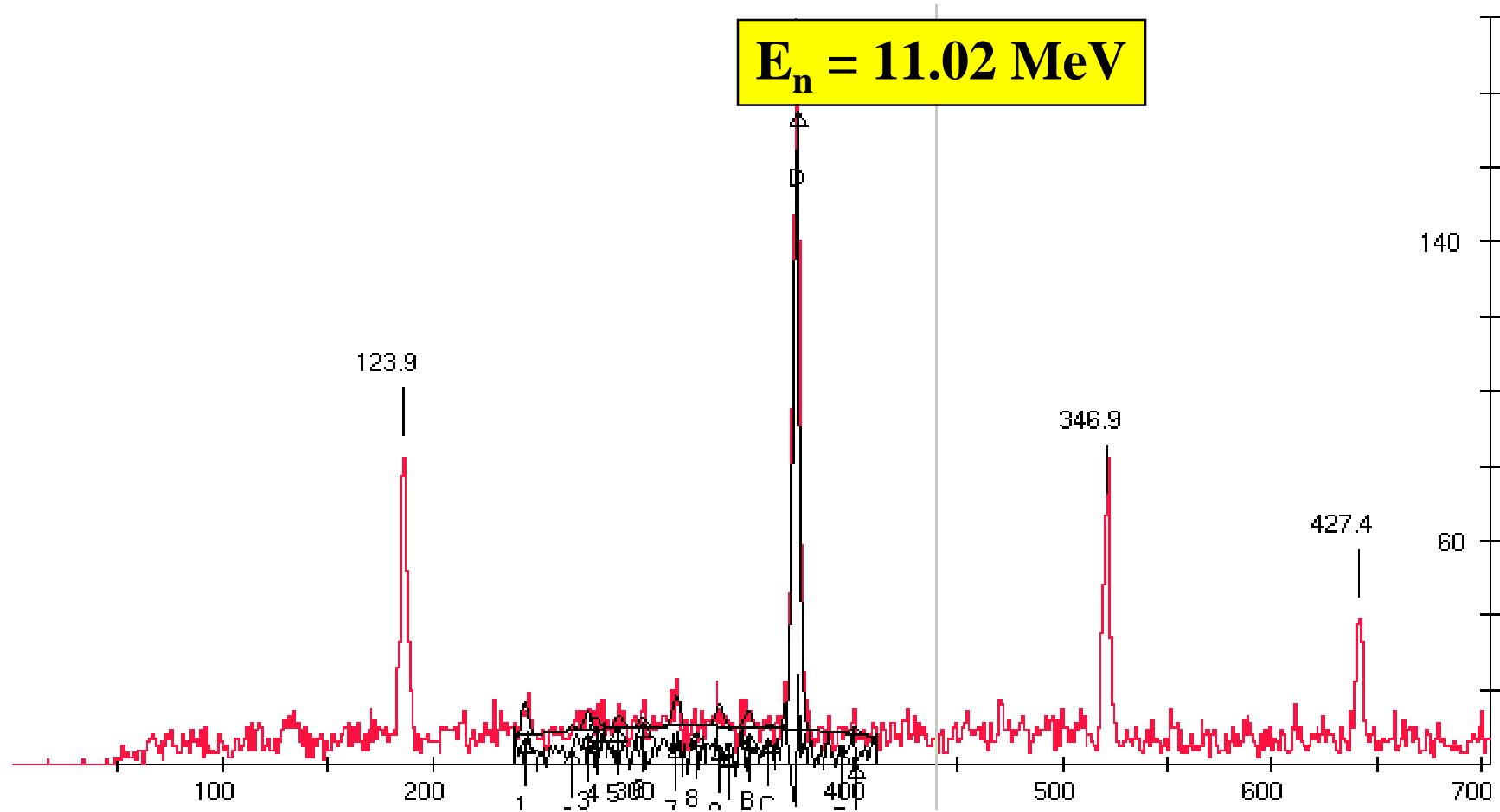
Gamma-spectrum in coincidence with different energy slices



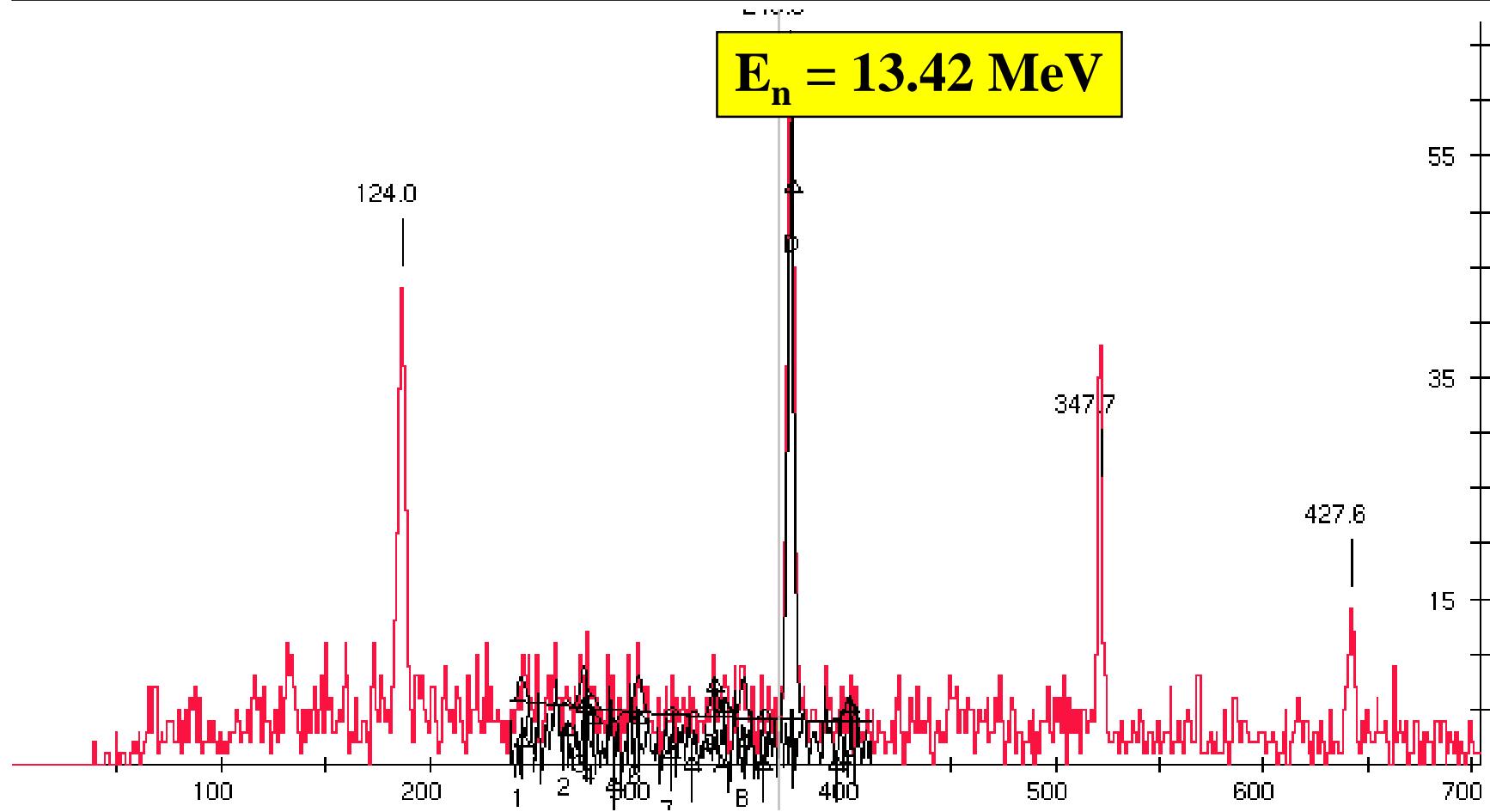
Gamma-spectrum in coincidence with different energy slices



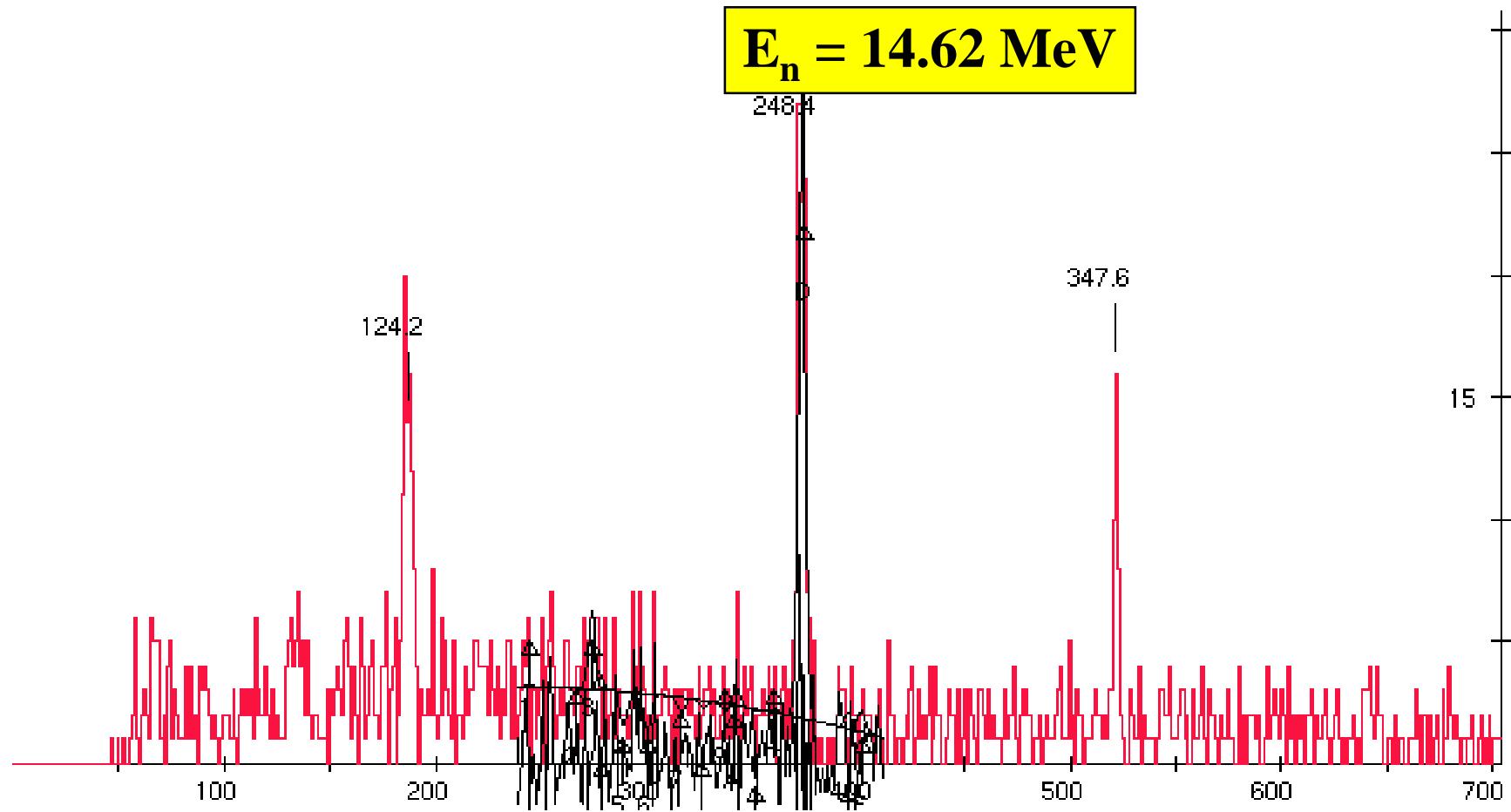
Gamma-spectrum in coincidence with different energy slices



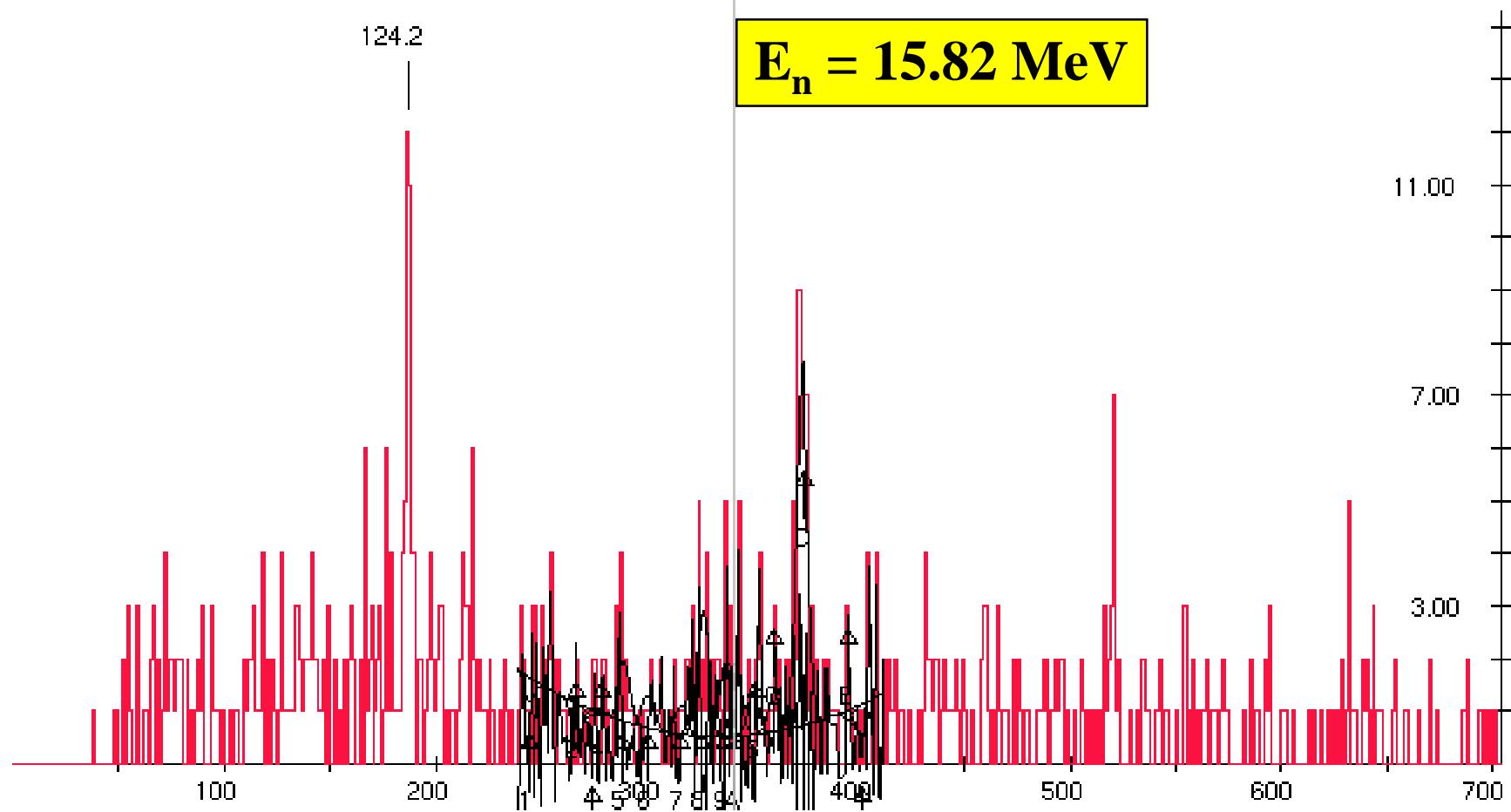
Gamma-spectrum in coincidence with different energy slices



Gamma-spectrum in coincidence with different energy slices



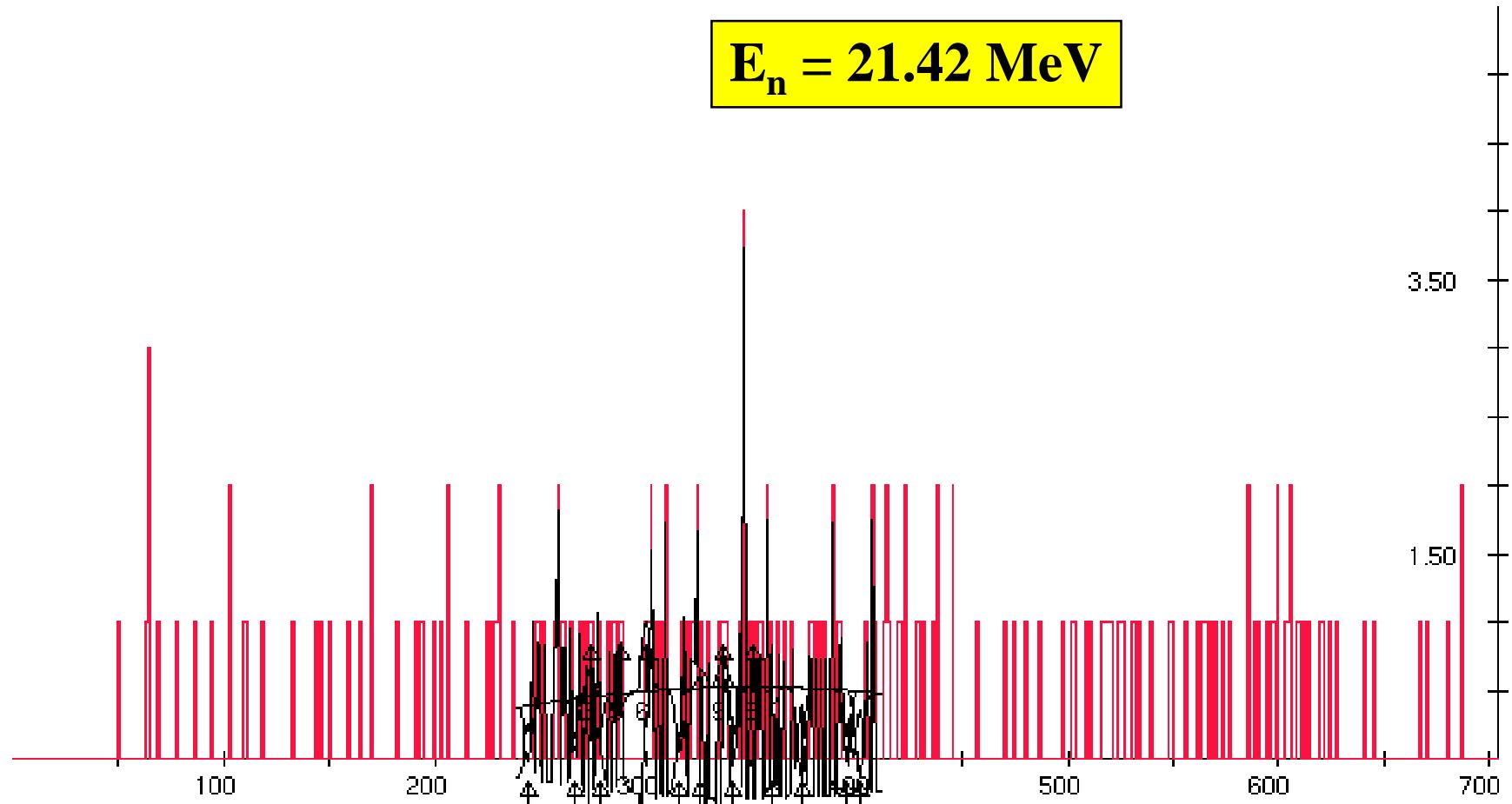
Gamma-spectrum in coincidence with different energy slices



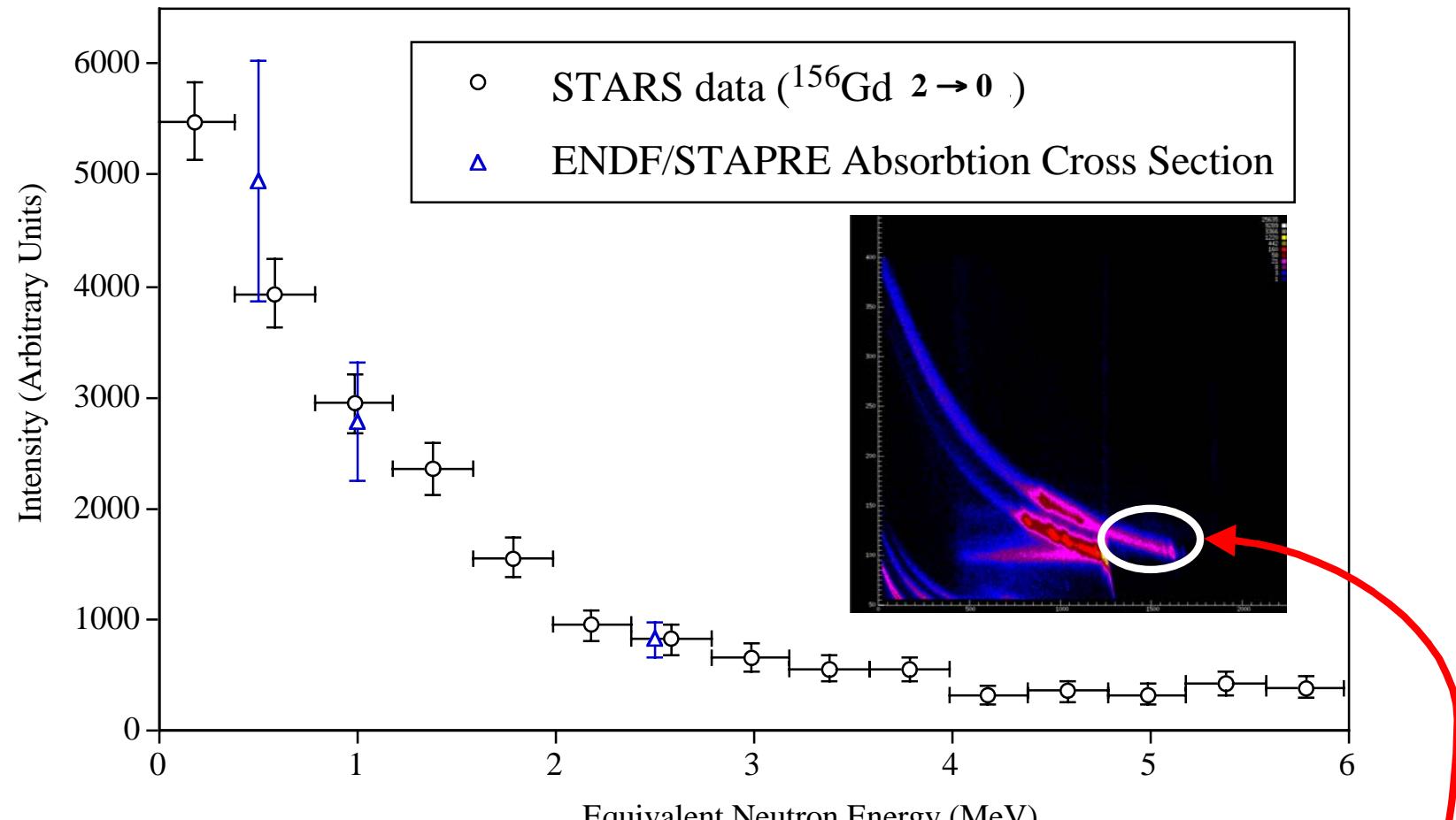
Gamma-spectrum in coincidence with different energy slices



$E_n = 21.42 \text{ MeV}$



Surrogate (n,γ) from STARS ($^3\text{He},\alpha$) data normalized using the α -particle spectrum



Unambiguous particle identification from energy ($Q=+14.2 \text{ MeV}$)

Surrogate cross section measurement using particle- γ coincidences



- Surrogate measurements are absolute probability measurements

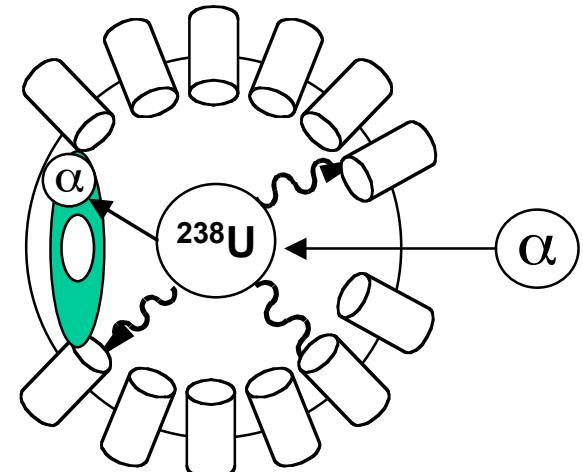
$$P_\gamma = \frac{L_\gamma \epsilon_{p-\gamma} (1+\alpha_\gamma) (\tau_{\text{total}}/\tau_{\text{dead}}) W(\theta)}{N_{\text{particles}}}$$

- Corrections must be made for effects that influence the numerator (γ -rays) and not the denominator (particles).
- Good particle-id required to obtain denominator.
 - Good resolution required, especially in the front detector.

Corrections terms for surrogate measurements using particle- γ coincidences



- Particle- γ efficiency ($\epsilon_{p-\gamma}$):
 - Use known particle- γ coincidences on target backing (C, N, O).
 - Double-checked using inelastic reactions on $^{51}\text{V}^*$
- Conversion coefficient ($\alpha_\gamma = N(e)/I_\gamma$):
 - Obtained from Hager-Selzer calculation
 - Depends on multipolarity and type of transition (i.e., M1, E2 etc).
Ground state band transitions in even-even Actinides are pure E2.
 - Very large near K-edge (≥ 10)
- Dead time (τ_{dead}):
 - Scale accepted & master triggers.
 - May already be in particle- γ efficiency



*Z.Phys. A321, 225 (1985)



Determining the denominator for $E_{\text{particle}} < E_{\text{beam}}$ using γ -rays only

- Contamination makes particle spectrum unusable for normalization
- Gamma's provide an unambiguous alternative

$$\frac{\sigma_{(n,xn)}}{\sigma_{\text{absorbtion}}} = \frac{\sum_{\substack{\text{Parallel} \\ \gamma\text{-rays}}} I_\gamma(n,xn)}{\sum_{\substack{\text{Parallel} \\ \gamma\text{-rays}}} I_\gamma(n,xn) + \sum_y \sum_{\substack{\text{Parallel} \\ \gamma\text{-rays}}} I_\gamma(n,yn)}$$

$$\frac{\sigma_{(n,xn)}}{\sigma_{\text{absorbtion}}} = \frac{1}{1 + \left(\frac{\sum_y \sum_{\substack{\text{Parallel} \\ \gamma\text{-rays}}} I_\gamma(n,yn)}{\sum_{\substack{\text{Parallel} \\ \gamma\text{-rays}}} I_\gamma(n,xn)} \right)}$$

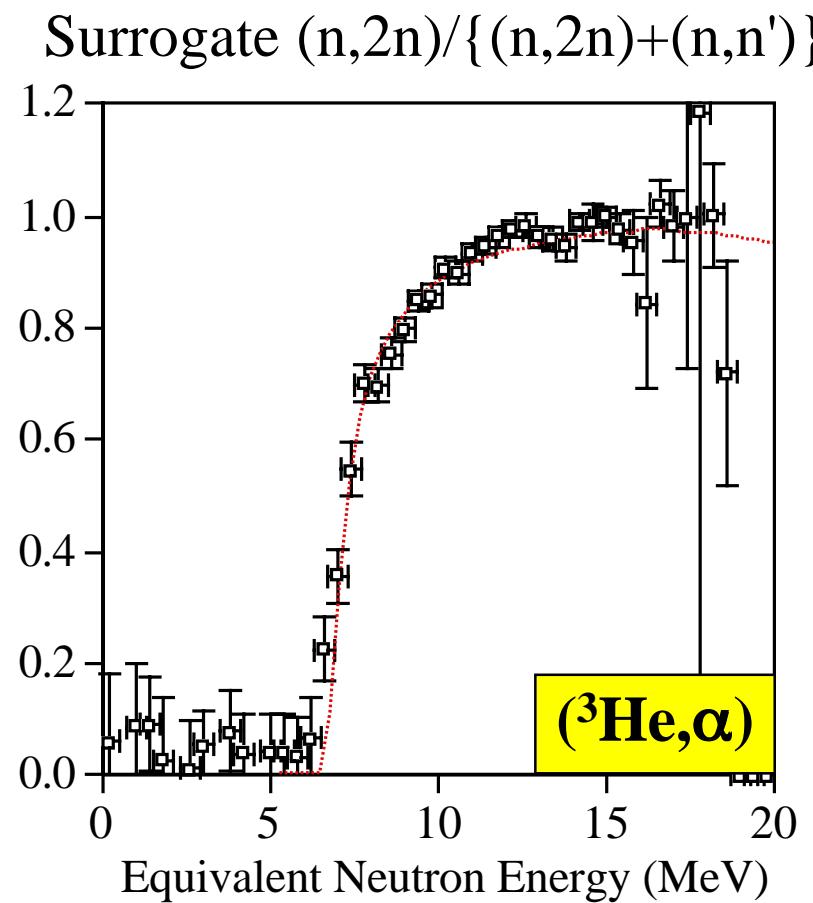
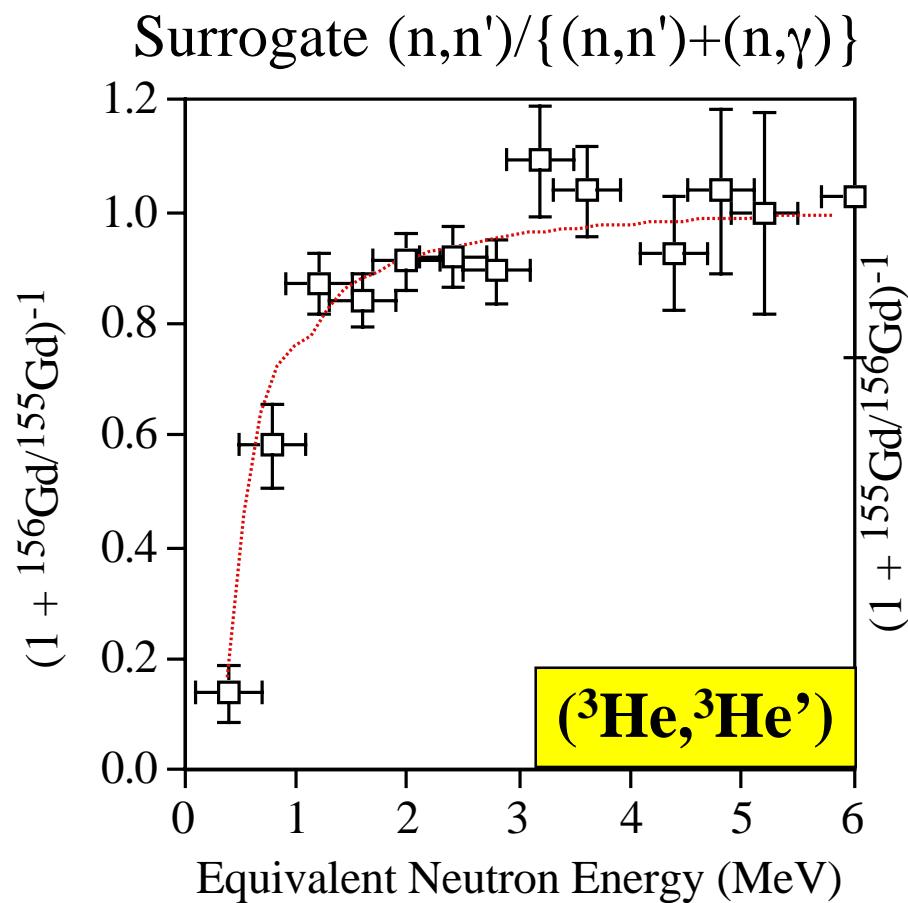
Comparison to Model Calculations



- Direct Model-Experiment comparison of γ -ray data allows for insight into J^π distribution and reaction modes.
- Hoffman et al., independently developed state-of-the-art neutron-induced reactions in the Eu-Gd-Sm radiochemical networks using the STAPRE reaction code
 - Residual nuclei determined using Hauser-Feshbach model
 - Continuum-Discrete level density mapping in residue γ -ray cascade
 - Output is low-lying discrete state partial γ -ray cross section
- Local systematics determined for $82 \leq N \leq 96$, 60 (Nd) $\leq Z \leq 66$ (Dy)
 - Level Densities (matched to values at S_n)
 - Optical Model (which determine γ , particle transmission coefficients)
 - Exciton pre-equilibrium model

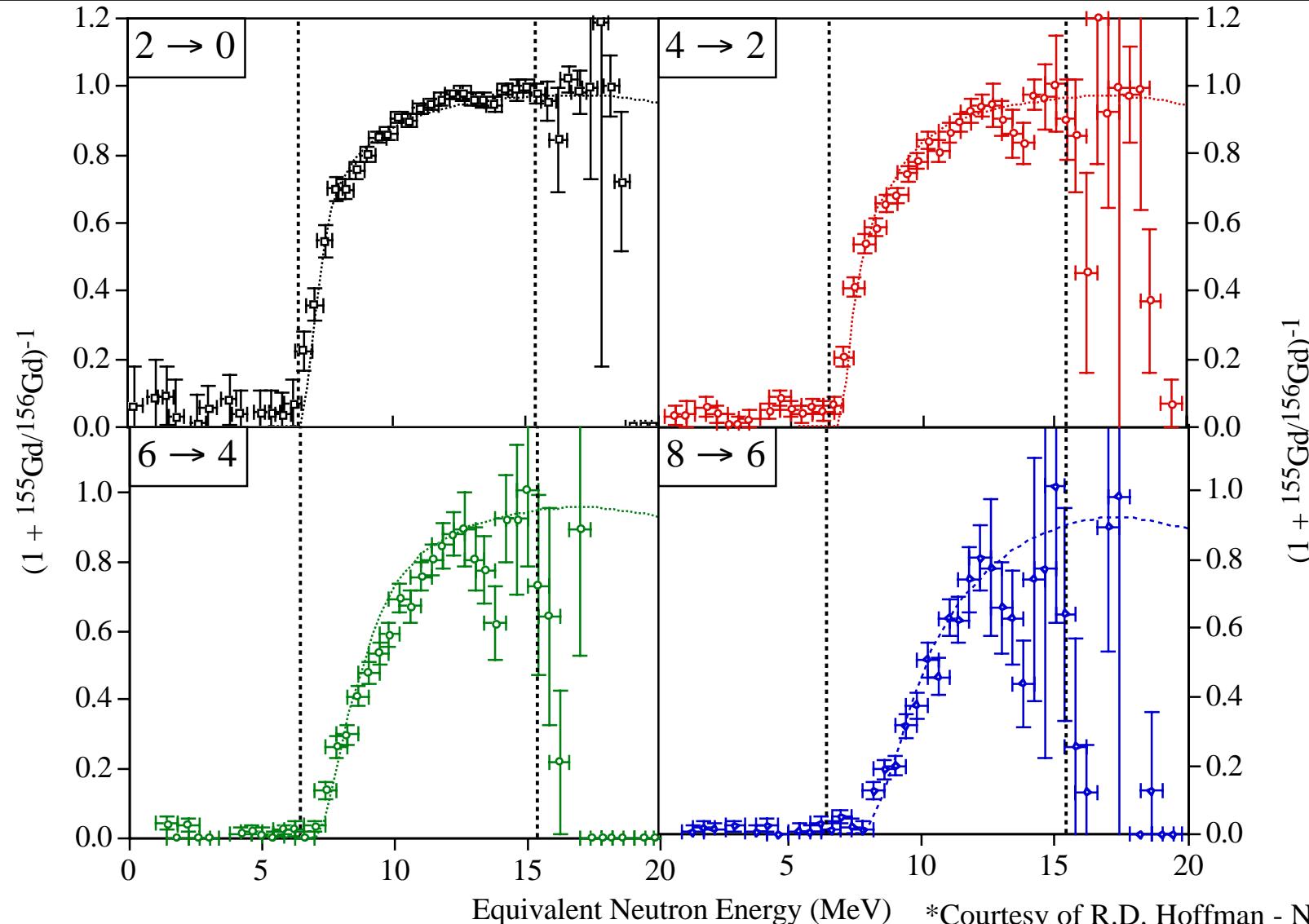
**STAPRE allows direct comparison to γ -ray data
(we lucked out!)**

Surrogate (n,n'), ($n,2n$) from STARS data compared to STAPRE calculations



Excellent agreement for both $(^3\text{He}, ^3\text{He}')$ and $(^3\text{He}, \alpha)$ reactions

γ -rays provide insight into angular momentum in the residual nucleus

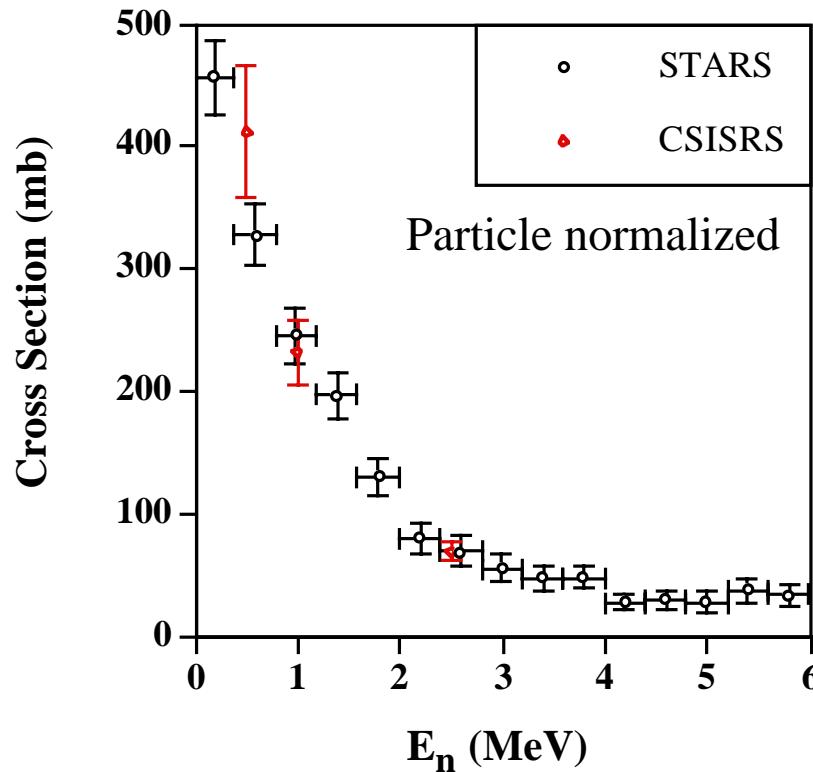


*Courtesy of R.D. Hoffman - NTM Group

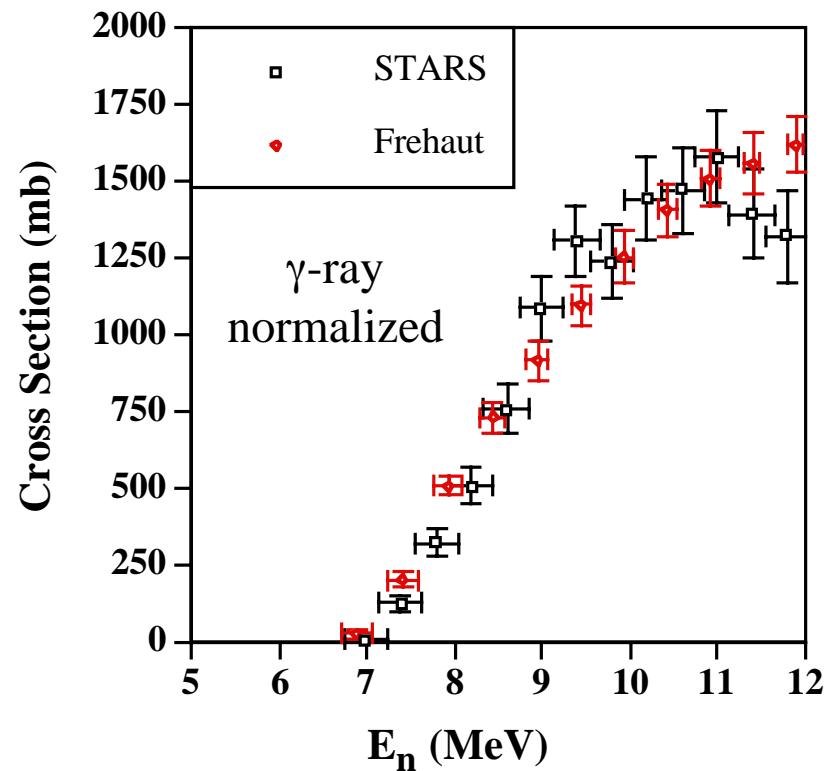
Converting Probability to Cross Section



Surrogate* vs. Measured $^{155}\text{Gd}(n,\gamma)^{156}\text{Gd}$



Surrogate* vs. Measured $^{155}\text{Gd}(n,2n)^{154}\text{Gd}$



*based on ^{154}Gd and ^{156}Gd $2^+ \rightarrow 0^+$ transitions only

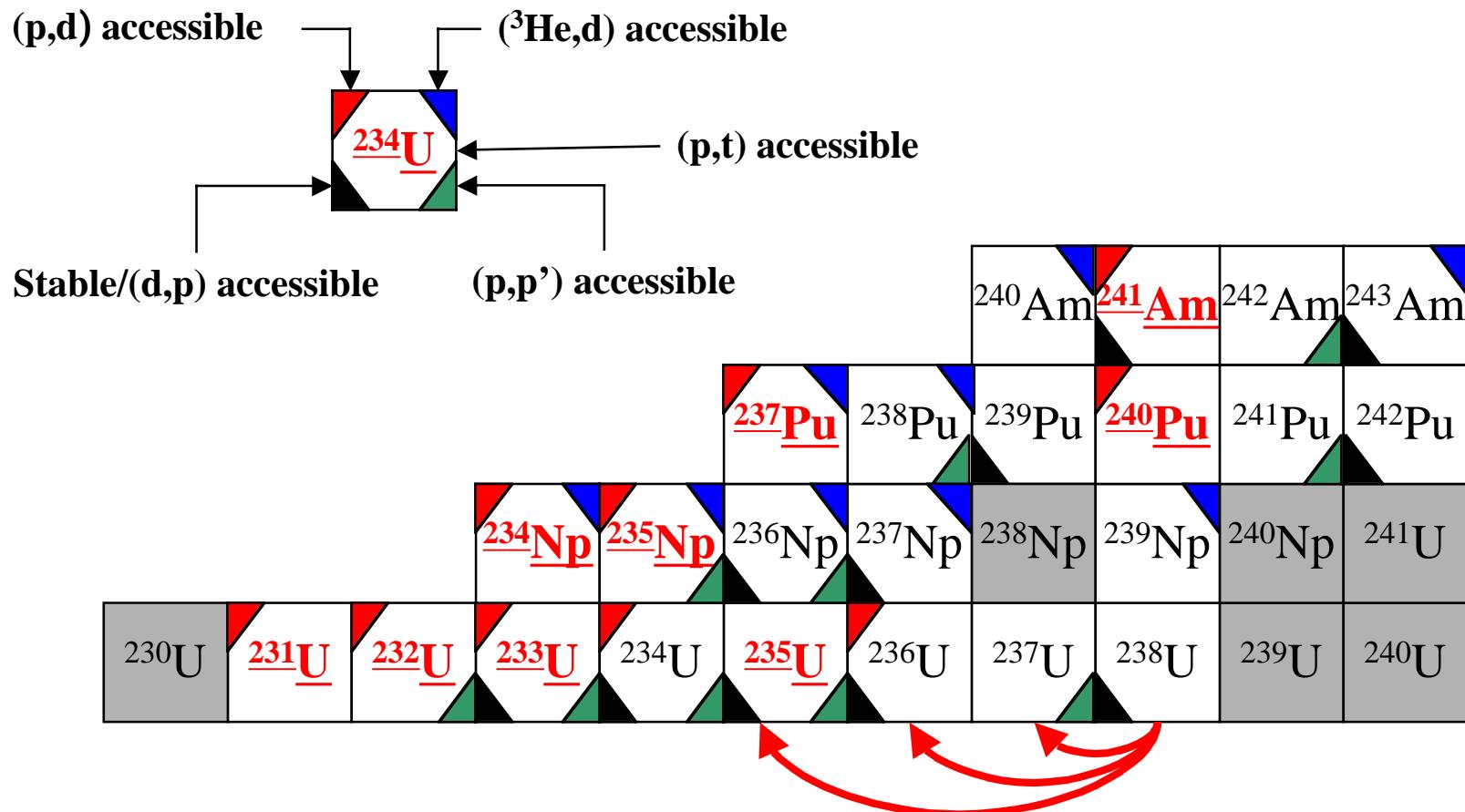
Weisskopf-Ewing Transformation

Fall 2003: A=90 surrogate neutron cross sections at Yale (Academic Alliance)



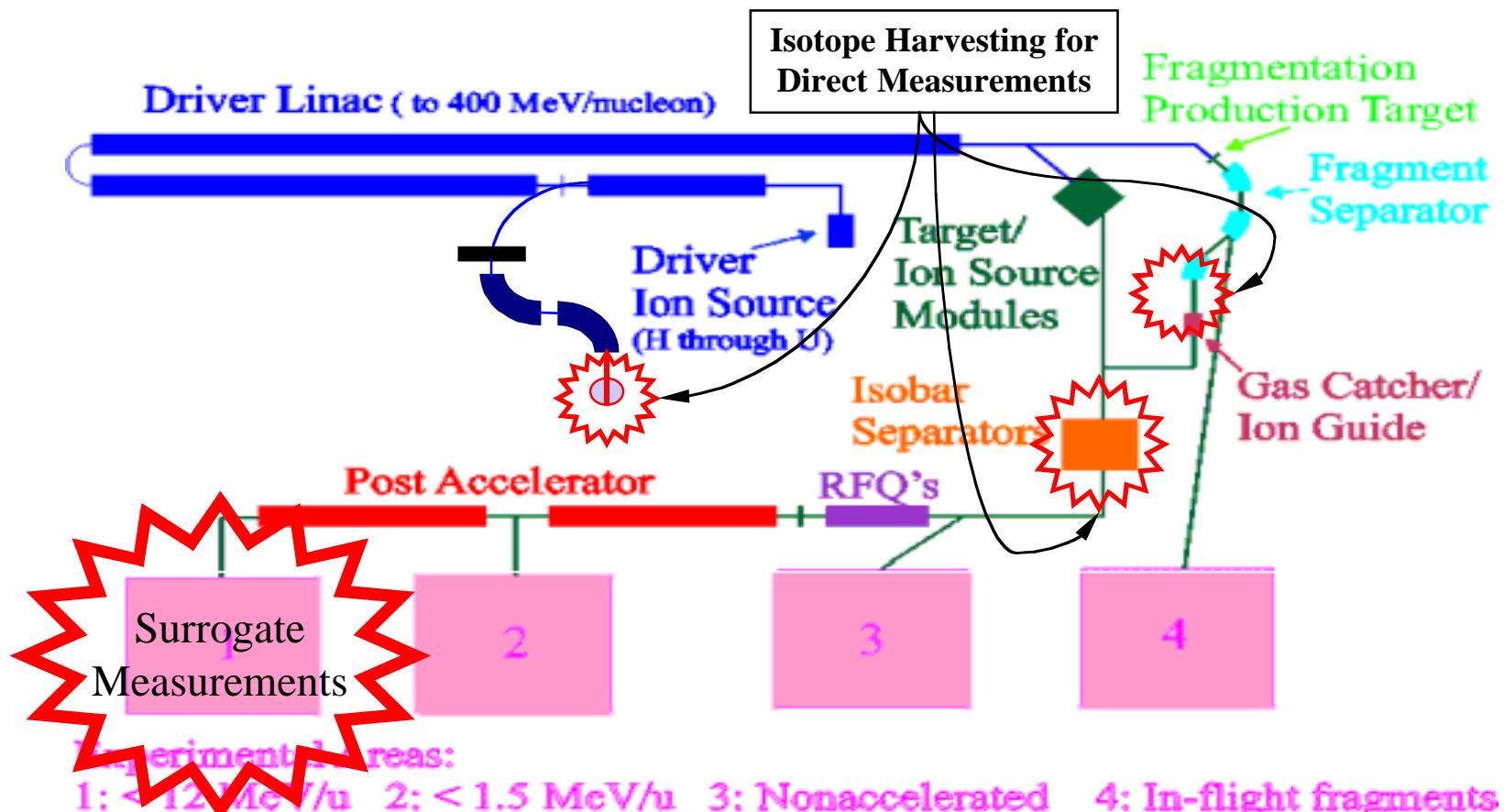
#	n-induced reaction	Charged particle surrogate reaction	Reason
1	$n + {}^{89}\text{Yb} \rightarrow {}^{90}\text{Yb} + x$ (Studied at GEANIE)	${}^{89}\text{Y}$ (d,px)	Best candidate reaction (same ν -doorway state, similar J).
2		${}^{88}\text{Sr}$ (${}^3\text{He}$,px)	Different doorway state (d instead of p).
3	$n + {}^{90}\text{Zr} \rightarrow {}^{91}\text{Zr} + x$ (Studied at GEANIE)	${}^{90}\text{Zr}$ (d,px)	See # 1.
4		${}^{92}\text{Zr}$ (${}^3\text{He}, {}^4\text{He}$) Cristina Plettner's talk this afternoon	Different angular momentum plus ν -hole instead of a ν -particle

The Next Step: Surrogate reactions for surrogate measurements on actinides



Jennifer Church's talk this afternoon

The Future: Surrogate Measurements at RIA



Develop now using stable (and some radioactive) beams